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BIM-Based Construction Waste Management and Circular Economy for Resource Recovery

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BIM-Based Construction Waste Management and Circular Economy for Resource Recovery

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

May 2021

Dedication

To my grandfather Antonio Chinelato, who taught me the importance of hard work, dedication, and perseverance through his life.

Acknowledgements

I feel extremely fortunate, and it is a genuine pleasure to acknowledge the many individuals that helped me achieve my doctorate degree.

To my advisor, Dr. Fernanda Leite, who is a great source of inspiration to me. She has been instrumental in my personal and professional formation, and I am forever grateful for all the advice, guidance, and many great opportunities that she provided me throughout these years. Specifically, the opportunity she gave me in the Summer of 2012 was a game-changer in my life and sparked my desire to join graduate school at UT. I am confident that her trust and encouragement were fundamental to navigate through the uncertainty of my PhD journey.

Dr. Kasey Faust, who gave me the opportunity to join the Green Fund project. This project was my opening door to the research world, and I learned enormously. I am very grateful for her close guidance in my first steps doing research and writing journal papers.

Drs. Juliana Felkner and Raissa Ferron, who provided me with their candor and technical advice, which helped to shape this dissertation.

I gratefully acknowledge the financial support from the Green Fund program at The University of Texas at Austin, as well as funding from the Construction Industry Institute (CII).

My dearest friends Gabriele Paladino, Deborah Cecatto, Heloisa Latham, and Hyun Jeong Koo who supported me throughout many years, listening, cheering, and taking my mind away from academia whenever I needed a break.

To Luis Daniel Beauperthuy, whose love made graduate school lighter and a beautiful chapter in my life. Thank you also for teaching me to take one day at a time.

My godmother Marcia Chinelato, and grandmother Irene Chinelato, who are constantly by my side despite our physical distance. Their prayers and encouragement are fundamental in my life.

To my brother, Paulo Guerra, who is the best brother I could ask for, and to my sister-in-law, Tatiane Hoshida. Thank you for always receiving me with hospitality.

Finally, to my parents, Ricardo Guerra and Marli Chinelato, who propelled me with their endless love, support and encouragement. They believed this was possible since the beginning and encouraged me to move forward during the rough times. I am forever grateful for your efforts and investments in me, and I am constantly inspired by you two.

Abstract

BIM-Based Construction Waste Management and Circular Economy for Resource Recovery

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The University of Texas at Austin, 2021

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Projections show that the consumption of raw materials worldwide is set to almost double by 2060, and the construction industry is a key responsible party for this trend. Additionally, high generation of construction and demolition waste is a common trend in the construction industry. Engineering challenges related to the aforementioned trends are identified in different phases of a construction project lifecycle. For instance, the difficulty in estimating construction waste (CW) generation in the early phases of a project and the lack of formal planning of CW reuse and recycling (R&R) during construction further challenges the waste generation issue. Moreover, early disposal of the existing built environment, with low recovery of resources are challenges associated to the end-of-life of projects that tend to aggravate the consumption of natural resources.

Three research questions in this PhD dissertation sought to aid the aforementioned engineering challenges. Research Question 1 is tied to the problem of CW generation estimation during *early phases* of the project; as such, algorithms leveraging Building

Information Modeling (BIM) were developed to automate and streamline CW generation estimations. BIM was used due to its capabilities of fast and reliable retrieval of project data. Research Question 2 built on Research Question 1 algorithms, but went one step further and discretized the amounts of CW generation into quantities for on-site reuse and off-site recycling. Four-dimensional (4D) BIM – through its simulation and visual capabilities – was used to enhance CW R&R planning *during construction.* Formalizing and enhancing CW R&R planning promotes resource recovery and minimizes waste disposal in landfills. Finally, Research Question 3 focused on the resource recovery issue at the *end-of-life* of a project, and the *design* of new building construction; this research sought to better understand the application of strategies that facilitate the circulation of resources in the United States built environment. Notably, contributions of this dissertation include streamlining the application of construction waste management practices (i.e., CW generation estimation and CW R&R planning) at the project level, and providing an overview of key construction industry stakeholders' awareness and adoption of circular construction strategies in the United States.

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Chapter 1: Introduction

Construction activity plays a vital role in a country's economy (ABC, 2017). Nonetheless, such high impact does not come without a price, and the construction industry and the built environment are known for extensive *natural resources consumption* and excessive *waste generation*. It is estimated that construction materials comprise approximately three-quarters of all raw materials use in the United States (Matos, 2017). Additionally, in 2017, construction and demolition (C&D) waste generation was more than twice the amount of municipal solid waste generation in the United States (EPA, 2019b). The aforementioned facts illustrate how the construction industry is traditionally rooted on a *linear economic model* (i.e., take-make-consume-waste) (Ellen MacArthur Foundation, 2013) – a model that contributes to environmental stress and unsustainable development.

Construction waste management (CWM) is a serious issue and addressing it is essential to drive the construction sector towards a more sustainable and resource efficient model. Peter F. Drucker (1954), known as the father of management, once said *"what gets measured gets managed"*. The research presented in this dissertation adopts the same philosophy and streamlines construction waste (CW) *generation estimation* through the use of Building Information Modeling (BIM) as a point of departure to better understand the CWM issue. Moreover, efforts are devoted to enhancing CW *reuse and recycle planning*; thus, promoting the circulation of resources in a closed-loop system as long as possible and minimizing CW directed to landfills. Better understanding these two components (i.e., CW generation, and CW reuse and recycling planning) is a stepping stone for the adoption of practices that are more aligned to the concept of *circular economy* (CE) – a paradigm that is opposed to the current linear economic model. The key insight behind circularity is that waste is not simply waste, but a resource. This view contrasts with the widespread and traditional view of waste as a non-good.

Different CE definitions and schools of thought are available in the literature (Anastasiades et al., 2020; Kirchherr et al. 2017; Ellen MacArthur Foundation, 2016; Cossu and Williams, 2015); nonetheless, common foundations of the model are based on a *better management of resources* and *waste minimization*. While the concept gained momentum over the last years, literature focusing on CE in the built environment is still in its infancy (Pomponi and Moncaster, 2017) – especially in the United States context. Therefore, the last piece of research in this dissertation focuses on understanding the adoption of circular construction strategies in the United States. This is especially important given increasing policies being implemented in Europe and Asia, which will impact the global construction market. In this chapter, engineering challenges associated with CWM and resource recovery in the built environment are investigated. Subsequently, the research vision and three specific research questions are presented. Lastly, a reader's guide of this dissertation is provided.

1.1 ENGINEERING CHALLENGES

Three major engineering challenges related to CWM and the built environment resource recovery are framed in this section. Each challenge is associated to a major phase of a construction project (i.e., planning and design, construction, end-of-life).

1.1.1 Construction Waste Generation Estimation

Various authors agree on the necessity of establishing a method for CW generation estimation to enhance the effectiveness of CWM practices (Lu and Yuan, 2011; Bakshan et al., 2015; Wu et al., 2014). This subsection is a compilation of barriers to the estimation of CW generation at the project level, especially during early stages of a construction project (i.e., planning and design).

The first barrier to CW generation estimation is the lack of a single universal methodology applied to projects of different types (e.g., residential, institutional), sizes, and construction technologies (e.g., pre-fabricated versus cast-in-place concrete elements). A plethora of different CW quantification methods is available in the literature and an in-depth review is provided in Chapter 2. Nonetheless, major challenges include: (1) methods that are time-consuming or require lengthy and complicated calculations; (2) methods that provide a rough estimate which is not detailed enough for the adoption of CWM strategies; (3) methods that rely on macro-level parameters (e.g., national building permits, population growth, construction activity of a certain area) and, thus, are not suitable for project-level estimates; or (4) methods that rely on waste generation rates (WGR) from different regions and countries, and therefore, are not universally applicable. This review of existing methodologies reveals the need to streamline CW estimation at the project level, during early stages of the project, and using data commonly available, and easily accessible by project management teams. This research gap is tied to **Research Question 1** and is presented in Section 1.2.

A second major barrier to CW generation estimation is the difficulty in data collection to *validate* the estimates. Not every construction project tracks its own CW generation data; for instance, small and/or medium projects that are not seeking environmental certification might not track this data at all. Other projects might track this data but not in a useful manner, which is the case of projects that report different waste streams commingled. This is problematic because proper tracking of CW generation provides a key foundation for implementing CW reduction programs and more proactive CWM practices. Additionally, tracking CW generation provides a source of ground truth data to benchmark projects and validate estimates performed in early stages of the project.

1.1.2 Construction Waste Reuse and Recycle Planning

C&D waste has a high potential for reuse and recycling (R&R) (Dominguez et al., 2016; Peng et al. 1997); nonetheless, until today, this potential has still not been thoroughly addressed (Anastasiades et al., 2020), and low rates of R&R are indicated as a limitation of construction projects. While several factors potentially contribute to low rates of R&R – e.g., cultural perception that reused/recycled materials are inferior (Rios et al., 2015); legislative and economic barriers (Ghisellini et al. 2018, Huang et al. 2018) – this subsection focuses on the challenges associated to *planning* CW R&R.

A construction waste management plan (CWMP) is a document intended to establish procedures for CW handling and mitigation measures. Although the benefits of a detailed CWMP are recognized, its implementation is challenged by the perception of loss of productivity and delay of other activities with higher priority in the project (Tam, 2008). Overall, CWM still is of lower priority when compared to other project goals, such as profit and meeting a completion deadline (Jain, 2012; Poon et al. 2001; Mahpour, 2018). A literature review of the 3R's (reduce, reuse, recycle) waste management principle and automated tools devoted to CWM planning (provided in Chapter 3) shows that few applications are devoted to formalizing CW R&R planning. Specific barriers include: (1) difficulty in the identification of construction activities able to admit CW for reuse; (2) difficulty in estimating CW amounts for on-site reuse and off-site recycling; (3) lack of a method that aids in *visually* planning CW R&R; and (4) poor team communication around the project's CWM goals. The aforementioned barriers are a hindrance to a more detailed and proactive CWMP. **Research Question 2**, presented in Section 1.2, is devoted to the challenge of CW R&R planning during the construction phase of the project.

1.1.3 Built Environment End-of-life and New Construction Circularity

An investigation of 227 commercial and residential buildings in the United States reveals that the majority of concrete buildings are disposed of before the end of their lives

(O'Connor, 2004). Moreover, a study of demolished buildings in Minnesota (United States) demonstrates that only 40% of these buildings were demolished due to deterioration of its physical conditions (Webster, 2007); therefore, corroborating with the perception that buildings tend to be disposed of before their intended life span (Cheshire, 2016). A circular building is the term used to define a "building that is designed, planned, built, operated, maintained, and deconstructed according to CE principles" (Pomponi and Moncaster, 2017). Unfortunately, the majority of the *existing* built environment was not designed in accordance to CE principles and with the purpose of facilitating resource recovery. In fact, very few buildings have been designed taking into account its end-of-life treatment (Rios et al., 2015). Therefore, the majority of materials end up as waste during the building's end-of-life, which increases the environmental costs and creates a risk of resource scarcity (Debacker and Manshoven, 2016; Mangialardi and Micelli, 2018).

Circular strategies aim to prolong the life of components and products (in this case, buildings), and close material flows once the end-of-life of this product is reached (Nussholz and Milios, 2017; Bocken et al., 2016). Several circular strategies are discussed in the literature (a review is provided in Chapter 4); however, the application of these strategies *in practice* is dependent on external factors and synergies between distinct stakeholders along the value chain (Wells and Seitz, 2005). For instance, when it comes to a building's *end-of-life* C&D waste management, factors such as landfill tipping fees, deconstruction labor speed and costs, presence of market for salvaged materials, and materials recuperation costs can largely influence – or hinder – the adoption of circular strategies by construction companies (Kibert et al., 2001). Similarly, in terms of new building construction, adoption of circular *design* strategies can be largely influenced by the designers' awareness of CE concepts, policies in place, and owners' requirements. One of the most popular group of studies related to CE in the built environment seek to assess the *awareness and adoption* of circular strategies by industry practitioners (Ghaffar et al. 2020; Mangialardi and Micelli, 2018; Adams et al. 2017). However, no study directed efforts to understanding the state of practice of circular construction in the United States context. As such, **Research Question 3**, presented in Section 1.2, is tied to this research gap.

1.2 Research Vision and Research Questions

The research presented in this dissertation focuses on the issue of CWM and resource recovery throughout a project lifecycle. Figure 1-1 is an illustration of my research vision following major phases of a construction project lifecycle.

I envision that CWM should receive as much attention as different project objectives, such as budget, schedule, and safety standards. For that, adoption of CWM strategies cannot be time-consuming or require extensive data collection, which hinders its potential to be widely adopted. Therefore, as a starting point, CW generation should be estimated with relative accuracy, during early stages of the project, and in an *automated* manner (Figure 1-1 – RQ 1). BIM is a technology suitable to streamline CW generation estimation due to its data-richness, collaborative interface, and reliable and automated quantity-take-off (QTO) capabilities (NBIMS, 2015; Monteiro and Martins, 2013). The accurate and straightforward estimate of CW generation provides a foundation for the implementation of CWM strategies in a project. However, besides the overall estimate of CW generation, it is necessary to estimate quantities of CW for on-site reuse and off-site recycling (Figure 1-1 – RQ 2A and RQ 2B). Notably, 4D-BIM is a powerful tool to visually demonstrate these quantities (i.e., CW generation, CW for reuse on-site, and CW for recycling off-site) and aid planning during construction. Proactively planning CW R&R enables maximizing resource recovery by down-cycling and up-cycling waste streams, and minimizing the amount of CW directed to landfills during the construction stage. Nonetheless, the completion of construction itself does not represent the end of the CWM and resource recovery issue.

In fact, a building's end-of-life stage is critical if we are to transition towards a more *circular and resource effective* built environment. If the end-of-life of the building is not carefully approached, the aforementioned strategies are reduced to a form of "delaying" the disposal of C&D waste into landfills. Several construction strategies aligned with a CE model (i.e., circular strategies) are available in the literature, however, the state of practice of their usage is yet to be explored in the United States context. As such, it is necessary to investigate the current state of practice of implementing a CE in the built environment in the United States. Specifically, it is necessary to understand the application of circular strategies at the end of a building's lifecycle, and during the design of new buildings (Figure 1-1 – RQ 3A and RQ 3B). Understanding the current adoption of these strategies and major challenges associated with their implementation is a necessary step towards achieving circularity in the built environment in the United States. Three research questions were developed to realize the aforementioned vision. Each research question is provided below:

Research Question 1: How can construction waste generation *estimation* be *streamlined* by leveraging BIM data during the early phases of a project?

- What type of data is necessary in a BIM to make construction waste estimation feasible during the early phases of a project?
- What type of external data (i.e., input) is necessary to make construction waste generation estimation feasible at the early phases of a project?

Research Question 2: How can construction waste reuse and recycle planning be *enhanced and formalized* during the construction phase of a project?

- How can we efficiently and effectively estimate the amount of construction waste that can potentially be reused on-site and recycled off-site?
- How can the dates and activities generating construction waste for reuse on-site be identified efficiently and effectively?

Research Question 3: What is the state of practice of Circular Economy in the United States building construction industry?

- How are companies dealing with the end-of-life of buildings? What strategies are being adopted in order to maximize resource recovery of building components?
- How aware are AEC industry stakeholders of circular strategies? To which extent are these strategies being implemented in new construction projects in the United States?
- What are the main barriers and limitations, as well as enablers in the adoption of circular strategies in both design and end-of-life phases of the project?

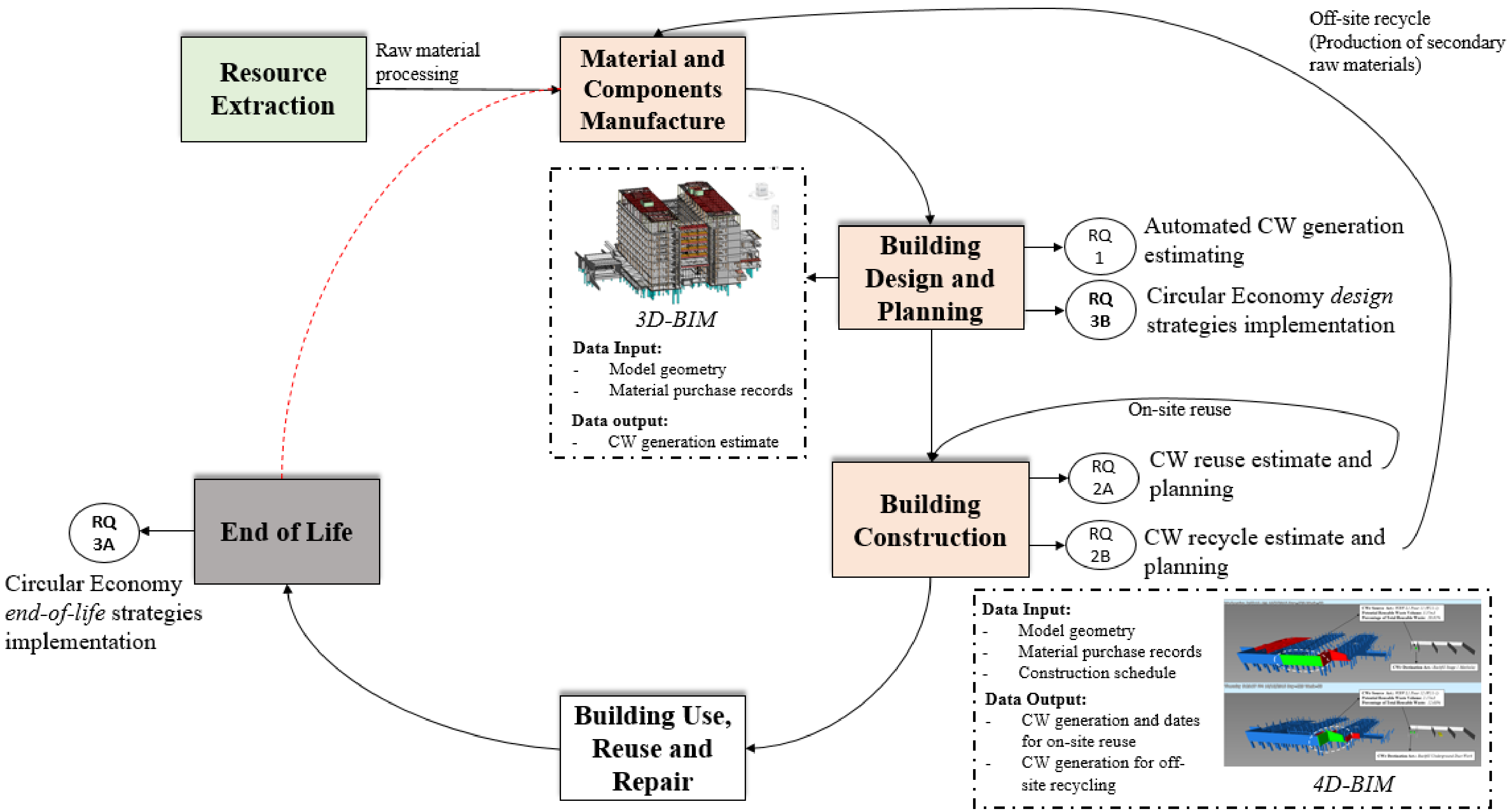


Figure 1-1: Research Vision

1.3 READER'S GUIDE TO THE DISSERTATION

This PhD dissertation is divided into five chapters. Chapter 1 presented the introduction, engineering challenges associated with CWM and resource recovery, the research vision, and three research questions. Chapters 2, 3, and 4 reflect each research question of this dissertation. That is, Research Question 1 is presented in Chapter 2, Research Question 2 is presented in Chapter 3, and Research Question 3 is presented in Chapter 4. Notably, Chapters 2, 3, and 4 are each written as stand-alone documents that contain an introduction, literature review, research method, results, and conclusions sections, reflection of a paper-based dissertation document. Finally, Chapter 5 summarizes the dissertation's conclusions and findings as well as future research.

Chapter 2: BIM-Based Automated Construction Waste Estimation Algorithms

This chapter has been published on Elsevier's *Waste Management Journal*. DOI: *https://doi.org/10.1016/j.wasman.2019.03.010*

2.1 INTRODUCTION

The construction industry is responsible for approximately 40% of natural resources consumption and waste generation each year in the United States alone (Agamuthu, 2008). Furthermore, construction and demolition (C&D) waste currently comprise 33–65% of the existing landfill space in the United States, Hong Kong, Canada, and the United Kingdom (Agamuthu, 2008). The consumption of natural resources for construction activities, coupled with the impact of dumping untreated C&D waste into landfills are examples of how the construction industry can contribute to the degradation of the environment (Mercader-Moyano, Ramírez-de-Arellano-Aguado, 2013). Part of the adverse effects of construction activities can be mitigated through the 3Rs principle of reduce, reuse and recycle. Having an estimation of the CW generated at the project level is of paramount importance for its management; that is, to determine how much can be reused, recycled, or finally disposed of in landfills. For this purpose, various construction waste quantification methodologies exist in literature. These reported estimation methods have limitations, including lack of precision, time-consuming implementation, lack of ground truth data, extended generalizations made, lack of means of verification to prove the appropriateness of the adopted methodology. As such, an efficient and effective methodology that uses reliable project data is necessary to attain more accurate and convenient CW estimation. Building Information Modeling (BIM), through its digital representation of physical and functional characteristics of a facility as well as its collaborative interface (NBIMS, 2015), offers an opportunity for fast and reliable CW estimation. In this chapter, BIM is leveraged to propose an automated CW quantification method, in which the CW is defined as the portion of materials purchased that is not incorporated into the actual building structure. The BIM material takeoff is used for the estimation of materials needed for the project, whereas the amount purchased is extracted from the project purchasing records.

CW estimation algorithms are developed to assess the generation of concrete and drywall waste streams, which are consistently on the top 3 largest CW streams produced in the United States in the previous years (EPA, 2015, 2016, 2018). Moreover, these two materials have unique characteristics—their purpose and stage of use in construction. While concrete is used at early stages of construction for structural purposes, drywall is used at later stages for finishing purposes such as enveloping or interior partitions. The proposed BIM-based CW estimation method is demonstrated on a pilot project of an institutional building complex project. The demonstration is enabled by the availability of the BIM models and the actual CW generation quantities for the pilot project. The availability of actual quantities provides an opportunity to validate the CW amounts estimated by the proposed method.

By relying only on automated BIM quantity takeoff (QTO) and purchasing records, applying the demonstration on a real-world project, and conducting the validation using ground truth data (i.e., actual CW generation quantities), the CW estimation method proposed in this chapter addresses the aforementioned limitations of existing estimation methods. By leveraging material quantities directly from BIM, CW estimation can be streamlined, enabling decision makers to implement more efficient CW management practices at the site level, without the barriers of developing much of the estimation manually.

2.2 Background Research

Numerous construction waste quantification methodologies exist in literature, as pointed out by Wu et al. (2014). Such methodologies can be divided into six major categories: site visit (SV), generation rate calculation (GRC), lifetime analysis (LA), classification system accumulation (CSA), variables modeling (VM), and other methods; in which the first four methods are the most commonly used, whereas the remaining are still at a conceptual level of development (Wu et al., 2014). Each of these methodologies have a recommended application (e.g., for the quantification of waste at regional level or project level, quantification of construction or demolition waste) and also have limitations. This section provides an overview of four methodologies (SV, GRC, LA, and CSA), followed by a discussion of existing automation of CW estimation efforts in the literature.

One of the most straightforward methodologies is the SV, which is based on project-level data collection and observations. Waste generation rates are typically calculated from the results of the site visit observations. Lau et al. (2008) and Poon et al. (2004) are examples of case studies that utilized site visit and observations in Malaysia and Hong Kong, respectively, for CW estimation. However, since project conditions—such as location and construction practices—vary significantly, the rates calculated from these methodologies often cannot be replicated unless the projects have similar characteristics. Furthermore, SV methodology is time consuming and rely on experience for proper implementation.

GRC approaches, on the other hand, which require obtaining a waste rate produced for a particular activity (usually in kg/m^2 or m^3/m^2) are the most applied methods (Wu et al., 2014). As such, GRC approaches can be performed based on different sources of data; McBean and Fortin (1993) utilized population growth in Canada to estimate the waste, Yost and Halstead (1996) utilized the financial value of building permits in the United States, and Lage et al. (2010) utilized construction activities and its area in Galicia. GRC is based on region-specific data, or macro-level variables (e.g., population growth, building permits issues, construction activity and region area), instead of project data. By relying on macro-level data, methods reported in these studies are not applicable on construction projects of varying types (e.g., residential, commercial, institutional) or their applications are limited to regions with similar construction techniques.

A branch of GRC are the CSA methodologies, which utilize classification systems and, thus, provide a more detailed waste estimation necessary for effective management practices. For instance, Solis-Guzman et al. (2009) utilized SV data and GRC combined to estimate CW in Spain, but the study utilizes region-specific data, which cannot be applicable to industries with different construction techniques.

LA approaches incorporate time and are grounded on the idea that the materials utilized for construction projects will eventually become waste once the lifetime of the building or materials is reached. Cochran and Townsend (2010) focused on the materials flow analysis (MFA) to estimate when materials will come out of service. Poon (1997) proposed a building lifetime analysis through case studies in Hong Kong. LA tend to be primarily implemented for the quantification of demolition waste, and not CW, because it assumes all the materials will eventually become waste, not distinguishing the portion of waste generated on construction phases. Additionally, LA approaches are based on amounts of materials consumed and buildings to be demolished on a certain region (another macro-level variable), thus, not being suitable to estimate CW at the project level.

In summary, SV is more suitable for project level estimation but can be time-consuming; GRC and CSA can be utilized at both the project and regional-level estimation but may be based on external data that cannot be suitable to different projects; and LA is more applicable for demolition waste instead of CW as it considers that all materials will eventually become waste and does not distinguish the amounts generated during construction phase.

As previously noted, in recent years, increasing attentions on waste management has led to the emergence of automated platforms that aid industry practitioners in decision making. The Site Methodology to Audit Reduced Target Waste (SMART-Waste) is a platform developed by the Building Research Establishment (BRE) at the United Kingdom used to help the construction industry monitor and report on areas such as waste generation and management, as well as site waste management plans (BRE, 2018). Intelex Waste Management (2018) is also a robust software that aids presenting waste management data in detailed reports and assists decision-making on disposal of waste. These software systems primarily aid in the benchmarking and decision-making areas instead of the quantification of the CW. In these platforms, the user is required to input the waste generated amount, which is often based on SV methods.

Besides the emergence of waste management software systems, efforts in automating CW estimation per se are also present in the literature. Li and Zhang (2013) developed a web-based CW estimation system for building construction projects using its work-breakdown structure (WBS). Wang et al. (2004) developed a Microsoft Excel-based approach to assist in the analysis and evaluation of C&D waste management from residential and commercial buildings in Massachusetts (United States). Limitations of the aforementioned studies are that Li and Zhang's (2013) web-based system requires manual entry of material volume quantity and the waste rates of each material, which relies on the accuracy of data provided typically by the project manager. Wang et al. (2004) utilizes RS Means to estimate the amounts of materials needed for the project which may not reflect actual data from a specific project. Furthermore, Wang et al. (2004) estimate the waste using a fixed waste rate factor of 10% of all the materials needed for the project, which also may also not reflect actual quantities.

None of the aforementioned studies achieved fully automation of CW estimation as one requires manual entry of data (Li and Zhang, 2013) and the other does not utilize actual project data (Wang, 2014). The popularization of BIM technology on the architectural, engineering and construction (AEC) industry, represents an opportunity to improve CW estimation as the BIM models are rich sources to retrieve actual project data in a fast and reliable manner. BIM has been increasingly explored for CW estimation purpose over the past years. Cheng and Ma (2013) developed a BIM-based tool to estimate and plan the waste generated from demolition and renovation. Kim et al. (2017) proposed a BIM estimation method for demolition waste that considers its classification type. Lu et al. (2017) created a tool to estimate waste during design and construction phases with the use of a BIM model. However, even with these attempts, gaps still remain literature. Cheng and Ma (2013) and Kim et al. (2017) focus on demolition waste and thus are not suitable for CW estimation, and Lu et al.'s (2017) tool is not able to provide the amount of CW by material (such as concrete, metal, plasters, etc), only by its components (e.g., basic wall, floor). Therefore, an automated approach able to estimate CW by material, requiring minimal external data, not based on regional databases, relying solely on the project quantities and records, able to suit various types of projects on different locations is still in need. Bakshan et al. (2015) proposes a concept in which the portion of materials purchased reduced by the portion of materials needed for the structure is considered CW. In this methodology, only the amounts of materials needed for the project and purchasing records are required; however, the quantity of materials needed is manually extracted from the structural drawings which makes the adoption of this approach time-consuming.

The parametric modeling capability of BIM models allows for performing diverse tasks, Monteiro and Martins (2013) states that one of the most useful tasks that can be automated through BIM use is the QTO. According to Ren et al. (2012), BIM-based QTO represents an easier, faster, cheaper and more accurate solution when compared with traditional QTO methods. In this context, the approach presented in this chapter couples Bakshan et al.'s (2015) methodology with a BIM-based quantity extraction for more accurate and convenient estimation of CW generation.

2.3 ALGORITHM DEVELOPMENT

In this chapter, two waste streams were selected to be focused on the development of the algorithms for its quantification: concrete and drywall. According to the United States EPA (2018), concrete represented the greatest part of C&D waste in 2015; it was the first waste stream by far with 70% of the total. When considering only CW, which is 10% of C&D waste, concrete is still the largest amount of debris. It is estimated that 23.1 million tons of concrete waste were produced only in construction activities in 2015, and buildings are the second largest source of this waste (only falling behind bridges and roads; EPA, 2018). Additionally, according to EPA reports (2015, 2016, 2018) drywall and plasters are consistently on the top 3 waste streams produced on construction activities. It is estimated that 2.5 million tons of drywall waste were produced in 2015 (EPA, 2018). As previously stated, this chapter proposes the adoption of the CW estimation concept defined by Bakshan et al. (2015), in which the portion of materials purchased reduced by the portion of materials needed for the structure is considered CW (Eqn. 2-1). This proposed approach is not considering whether these surplus materials were used for other purposes on-site and were not disposed, for instance.

$$CW = \sum_{\text{Purchased}} - \sum_{\text{Needed}} \qquad \textit{(Eqn. 2-1)}$$

On the first part of the equation, the amount of materials purchased is often available in the general contractor's purchasing records. On the other hand, the amount of materials needed for the project can be estimated from the BIM model QTO. In this approach, the amount needed is assessed using material quantity data extracted directly from BIM models of a real-world project.

2.3.1 Concrete Waste Algorithm

For this algorithm, cast-in-place reinforced concrete structure is assumed. This type of structure has five sources of concrete waste: foundation piles, columns, beams, slabs, and stairs. Only the structural elements of the building itself were considered in this approach. For instance, retaining walls were considered a part of site preparation, or work done previously than the building structure. Eqn. 2-2 is used to estimate the actual amount of concrete needed for each structural element category aforementioned, in which the actual amount of concrete is the volume of the element reduced by a specific reinforcement rate multiplied by the volume of the element. Appendix B contains a list of 3D model requirements for the concrete algorithm.

$$\sum_{\text{Actual Concrete St. Element}} = \sum_{\text{Vol. Concrete St. Element}} - \left(St_{\text{Reinforcement Rate}} * \sum_{\text{Vol. Concrete St. Element}}\right)$$

(Eqn. 2-2)

Most BIM have only the geometry of the structural elements, even though reinforcement detailing is often available in the software systems. One limitation is that actual reinforcement quantities could not be quantified on the 3D BIM. As such, a rate of reinforcement per volume of concrete was assumed for each structural element—2% for foundation piles, columns, beams, and 1.5% for slabs and stairs, based on the characteristics of the building. These rates are validated by a Registered Professional Engineer, specialized in Structural Materials. The overall concrete waste can be calculated using Eqn. 2-3 in which the amount of concrete purchased is reduced by the sum of the actual amounts of concrete needed for each structural element category.

$$CW_{Concrete} = \sum_{Concrete\ Purchased} - \left(\sum_{(1\ to\ 5) Actual\ Concrete\ St.\ Element}\right) \qquad \textit{(Eqn. 2-3)}$$

The concrete waste of Eqn. 2-3 is reported in volume (cubic feet or cubic meters), which is suitable to quantify the amount of dump trucks needed to transport the waste to the landfill. In order to provide also the amount of concrete waste by weight (in pounds or kilograms), the concrete waste is multiplied by the concrete density (145 lb/cubic feet or 2,322.68 kg/m^3; ACI Committee 318, 2014) and is shown in Eqn. 2-4.

$$CW_{Concrete\ Weight} = CW_{Concrete} * D_{Concrete} \qquad \textit{(Eqn. 2-4)}$$

2.3.2 Drywall Waste Algorithm

The quantification of the square footage of drywall needed for the project is calculated by filtering on the BIM model all the walls that contained "Gypsum" as material (refer to Appendix B for 3D model requirements for the drywall algorithm), and these quantities are already discounted by the spaces such as doors and windows. The amount of drywall waste for the project is shown in Eqn. 2-5, where drywall actual is the amount of drywall retrieved from the model (in square foot or square meter), and drywall purchased is the amount of material purchased (in square foot or square meter) by the contractor to perform the work.

$$CW_{Drywall} = \sum Drywall_{\text{Purchased}} - \sum Drywall_{\text{Actual}} \qquad \textit{(Eqn. 2-5)}$$

The drywall waste of Eqn. 2-5 is reported in square foot or square meter, in order to provide the amount of waste by weight (in pounds or in kilograms), the waste is multiplied by the drywall weight per square foot as shown in Eqn. 2-6. Different types of drywall are available in the market (e.g., lightweight, fire resistant, moisture resistant, regular) with specific purpose applications. Only the weight per square foot is relevant to make a distinction between the products on this algorithm. Still, according to the products specifications of one of the largest drywall manufacturers in the United States, the variance of weight per square foot between the products is not very expressive, and thus an average weight of the material was considered for all gypsum walls on this project

(2.45 lb/square foot; equivalent to 11.96 kg/m^2). This number also falls in accordance with the weight reported by the Gypsum Association (2017).

$$CW_{Drywall\ Weight} = CW_{Drywall} * W_{Drywall} \qquad \textit{(Eqn. 2-6)}$$

2.4 DEMONSTRATION OF THE PROPOSED ALGORITHMS

In order to demonstrate and validate the proposed algorithms, this chapter uses a real-world project of an institutional building complex. The building has over 430,000 square feet of open and flexible space for interactive learning; with state-of-art laboratories, open and closed spaces for study, a cafeteria and a library. Attached to the south side of the building is a large auditorium with a 300-seat capacity. The construction of the complex started in 2015 with substantial completion in August 2017.

The building has eight levels in which the first three are integrated and the remaining five levels are separated into two towers (South and North), as shown in Figure 2-1. Cast-in-place concrete was used for the structural framing. The majority of the walls are composed of metal studs and drywall, with a few made of concrete masonry units (CMU). The towers are connected by corridors for users to cross from one side to the other. Aluminum panels create an enclosed atrium space.

The use of this building for a case study was suitable due the availability of structural and architectural BIM models, and the availability of quantities purchased by the general contractor. The validation of the amounts retrieved from the BIM models is performed with aid of a cloud-based software named Assemble. The validation of the estimated concrete waste is possible due the record of truckload tickets during construction, which is reported in Bakchan and Faust (2019). The validation of the estimated drywall waste is performed based on literature numbers, as for this particular pilot project, drywall was commingled with trash waste and not separately reported in the truckload tickets.

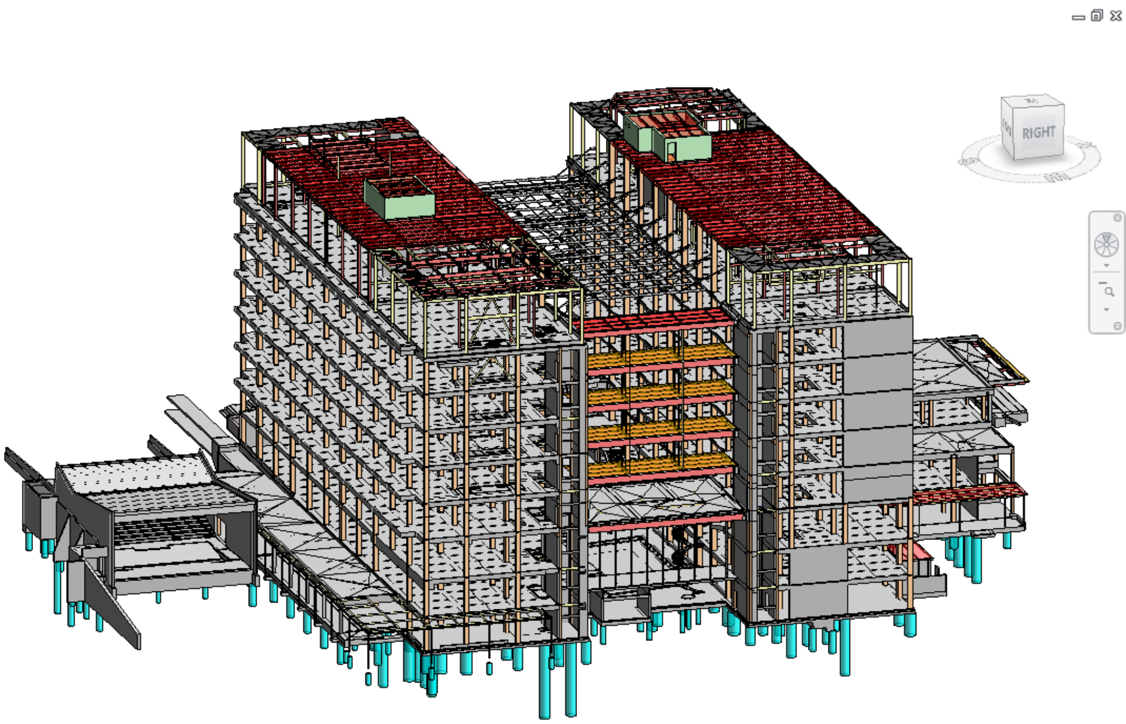


Figure 2-1: Structural model of pilot building project

The representation of the concrete and drywall waste algorithms are shown in Figure 2-2. For this building, the architectural and structural BIM models were separated.

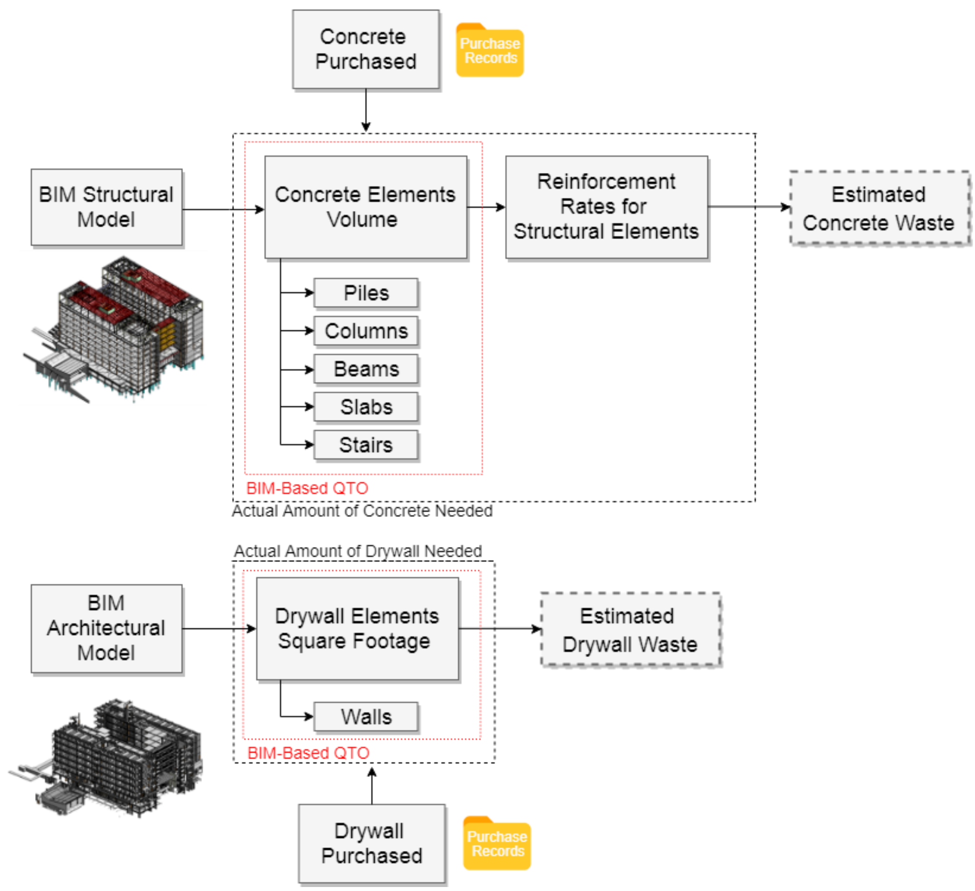


Figure 2-2: Representation of the concrete and drywall waste quantification algorithms

2.4.1 Concrete and Drywall BIM-based Material Takeoff and Validation

The volume of concrete needed for the structural elements of the building (foundation piles, columns, beams, slabs and stairs) were retrieved from the 3D BIM of the pilot project (Table 2-1) – refer to Appendix C for a detailed concrete QTO demonstration. These quantities were validated using Assemble, a cloud-based software that extracts model information, enabling stakeholders to visualize BIM model quantities on a browser and export to a Microsoft® Excel spreadsheet.

Structural Element	Concrete Volume extracted from BIM model (Cu ft)	Concrete Volume on Assemble (Cu ft)	Variation (%)
Piles	48,996.07	48,996.09	0.00
Columns	46,372.99	46,283.40	0.19
Beams	179,940.25	179,947.17	0.00
Slabs	236,694.62	236,814.57	0.05
Stairs	863.61	860.76	0.33

Table 2-1: Internal validation between local and cloud-based concrete quantities

Table 2-1 also shows the variation of the quantities between the 3D BIM and the cloud-based software. In all structural elements categories, the difference was less than 1% and therefore the numbers estimated by the 3D BIM using the "Material Takeoff" function are considered consistent. Table 2-2 shows the calculation of the actual amount of concrete needed for each category of structural element on the project. On this table the amounts found on the 3D BIM model for each category of element are discounted by the reinforcement rates assumed on the algorithm - 2% for foundation piles, columns, beams, and 1.5% for slabs and stairs.

Structural Element	Concrete Volume extracted from BIM model (Cu ft)	Actual Volume of Concrete Needed (Cu ft)
Piles	48,996.07	48,016.15
Columns	46,372.99	45,445.53
Beams	179,940.25	176,341.45
Slabs	236,694.62	233,144.20
Stairs	863.61	850.66
Total	512,867.54	503,797.99

Table 2-2: Calculations of the actual amount of concrete needed for the project

The actual area of drywall needed for the project was retrieved from the architectural version of the 3D BIM – refer to Appendix C for a detailed drywall QTO demonstration. As previously stated, the numbers found in the BIM through the "Material Takeoff" function for drywall already discounts spaces such as doors and windows, and therefore there is no need to subtract anything from this quantity. The square footage of drywall retrieved from the 3D BIM model was validated in the cloud-based software and Table 2-3 shows the numbers assessed by software system.

Element	Drywall Area extracted from BIM model (Sq ft)	Wall Area on Assemble (Sq ft)
Drywall Wall	1,031,159.19	503,471.93

Table 2-3: Internal validation between 3D BIM and cloud-based software drywall quantities

It is important to note that the 3D BIM square footage is approximately double the value found in the cloud-based software. This difference is due the fact that the model was set intended to provide the area of material, whereas the cloud-based software gives the area of the wall elements. The numbers found in the 3D BIM QTO already considers both sides of the wall for the amount of material, whereas the cloud-based software only considers one side of the wall. Taking this into consideration, both resources vary by less than 1%.

2.5 RESULTS AND DISCUSSION

The calculation of the actual amount of materials needed for the project is demonstrated in the previous section. This section demonstrates the estimation of waste generated, which uses the amount of materials purchased by the general contractor. The concrete and drywall amounts purchased were collected with the project manager and are shown in Table 2-4, as well as the final estimation of waste generated.

Material	A) Amount Purchased	B) Actual Amount Needed	C) Estimated Waste C= A-B	Percentage of Waste from Amount Purchased
Concrete (Cu ft)	513,800.00	503,797.99	10,002.01	1.95%
Drywall (Sq ft)	1,196,000.00	1,031,159.19	164,840.81	13.78%

Table 2-4: Amounts purchased and estimated waste

From Table 2-4, 725.15 tons of concrete waste are estimated. According to Bakchan and Faust (2019), concrete and masonry waste were combined on this project. However, the majority of concrete waste generation took place during the foundation and structural concrete stages, whereas the masonry waste stream is generated during the masonry work and finishing stage of construction.

According to Bakchan and Faust (2019), a total of 652.91 tons of concrete is generated during the foundation and structural concrete stages. When comparing the estimated (725.15 tons) and the actual concrete waste, there is a variation of 11%. This variation indicates that the estimated CW was greater than the actual concrete waste that left the site, which might occur due to various reasons; e.g., variability between the exact location of formwork and its designed position, which might have caused extra concrete to be poured on the structure, residual concrete in truck-mixers, residual concrete in buckets, lost concrete material during transportation to the work face at the jobsite, over pouring in uneven surfaces, such as grade beams, among others. This may have not been included on the truckload tickets. From Table 2-4, 1.95% waste from the amount of concrete purchased was estimated; this number falls in accordance to the literature, which can be as low as 1% or as high as 13.2% depending on the country (Kazaz et al., 2015).

As previously stated, on this particular pilot project, drywall waste was commingled with trash waste and thus the truckload tickets cannot be used for the validation of this material. From Table 2-4, 13.78% waste from the amount of drywall purchased was estimated, which is close to the statistics of drywall waste in the United States and North America. According to Cochran and Townsend (2010), an average of 10% of the drywall purchased for construction is wasted during construction activities. Ndukwe and Yuan (2016) state that in North America, approximately 12% of new construction drywall is wasted during installation. Data from the Michigan Government (2007), also supports the 12% waste on drywall activities during construction. Furthermore, both purchased waste percentages of concrete and drywall are also close to the estimated by Bossink and Brouwers (1996) in which about 1-10% of the construction materials purchased by general contractors leave the site as waste.

Implementation of CW management practices requires reliable estimation of the amounts of waste produced at the project level. While diverse estimation methods are available on the literature, those that are time-consuming or require extensive external sources of data suffer the risk of being disregarded by industry practitioners. Metrics comparing the proposed CW estimation methodology to other automated or BIM-based CW estimation methodologies existing in literature is shown in Table 2-5.

Metric	Automated and BIM-based Methodologies in Literature		Proposed BIM-based Methodology
Data Source(s)	Li and Zhang (2013)	• Waste levels for each material and activities on the WBS were obtained through personal interviews and based on other research on Hong Kong public housing projects	• Material quantities are extracted from BIM models
	Lu et al. (2017)	• A database that stores waste generation rates (WGR) for each of the BIM elements. Material quantities are extracted from BIM models	
	BRE (2018)	• User has to input waste data	
Applicability to different project types (e.g., residential, institutional)	Li and Zhang (2013)	• The waste levels assumed might not reflect the reality for different types of projects	• Yes, as long as the project has BIM models. No update is needed to apply the algorithms from one model to other
	Lu et al. (2017)	• Yes, as long as the project has BIM models; however, the database of waste by elements might need to be updated depending on the model	
	BRE (2018)	• Yes, user can use the tool for different projects	

Table 2-5: Qualitative comparison between automated and BIM-based methodologies in literature and proposed BIM-based methodology

Classification of the waste by material type	Li and Zhang (2013) Lu et al. (2017) BRE (2018)	• Yes, the tool provides the waste by material type. Also, it provides various options for the user to select how he wants the waste to be shown (e.g., by stream, by work package, by origin) • No, the tool provides the total waste produced on the project, or the waste produced by each element of the project (e.g., floor, columns, walls) • Yes, user has to input the waste by material when reporting	• Yes, the algorithms are created for each waste stream and therefore it is already classified
User input require	Li and Zhang (2013) Lu et al. (2017) BRE (2018)	• Extensive, user has to manually develop a WBS for the entire project, add the materials descriptions, and add the quantities required for each element of the WBS • None, however database of WGR might need to be updated according to the BIM model • Extensive, user has to input product details such as code, dimensions and quantities	• One user input for each algorithm. Purchasing records from the general contractor

Table 2-5, continued: Qualitative comparison between automated and BIM-based methodologies in literature and proposed BIM-based methodology

2.6 Conclusions and Future Research

In this chapter, two straightforward and effective, algorithms were developed and demonstrated for the quantification of concrete and drywall in a real-world project. The main contribution of the proposed algorithms is the use of only linear equations, BIM-based QTO, and project purchasing records for estimating CW generation at the project level. Also, the estimations performed with the proposed algorithms were validated based on ground truth data related to CW quantities reflected in the truckload tickets for the case of concrete waste stream and reported estimates in literature for the drywall waste stream. The concrete waste estimated for the pilot project had a variation of 11% from the actual quantities recorded on the truckload tickets, which may have happened due various reasons discussed. Estimates of 1.95% and 13.78% of waste from the amounts of concrete and drywall purchased respectively by the general contractor were assessed, which falls in accordance with literature reported estimates. Furthermore, this chapter focused on BIM's ability to provide a reliable QTO of the materials needed for the project, which is an important part for CW estimation. Validation of the BIM-based QTO was performed with the aid of a cloud-based software and numbers were consistent, with a variation of less than 1% between the two software systems.

Future work should include substituting percentages of reinforcement rates by actual reinforcement amounts, thus improving the accuracy of the concrete algorithm. This improvement could occur with the integration of the BIM model and the structural software system that contain actual data of reinforcement for a specific project. This improvement would increase the accuracy of the estimation which could ultimately aid general contractors in finding factors that cause concrete waste on-site (e.g., the quality of the formwork and amount of leftovers, the quantity lost or consumed on pump, bucket or other transportation sources, or even excessive surplus material purchasing practices).

Since contractors buy standardized drywall pieces and then perform cutouts needed for the project (e.g., doors, windows), some waste cannot be avoided. One improvement on the drywall algorithm could be in calculating this expected waste and comparing it to the actual generated quantity. This separation between the expected and actual waste could aid construction industry practitioners in drawing conclusions about the waste level on-site, perhaps due to rework or current workforce practices.

Chapter 3: 4D-BIM to Enhance Construction Waste Reuse and Recycle Planning

This chapter has been published on Elsevier's *Waste Management Journal*. DOI: *https://doi.org/10.1016/j.wasman.2020.07.035*

3.1 INTRODUCTION

The construction industry is perceived as a major contributor to environmental degradation (Lu and Yuan, 2011). Beyond excessive natural resources consumption, the construction industry is responsible for massive amounts of construction and demolition (C&D) waste directed to landfills each year. In 2017, 569 million tons of C&D waste was generated in the United States (EPA, 2019a), and although C&D waste has a high potential of reuse and recycling (R&R) (Dominguez et al., 2016; Peng et al. 1997), it is estimated that only 40% of building-related C&D waste generated is reused, recycled, or sent to waste-to-energy facilities (EPA, 2009a). Furthermore, despite efforts of increasing R&R, it is estimated that 35% of C&D waste produced globally is directed at landfills without any further treatment (Menegaki and Damigos, 2018). Notably, maximizing the R&R of C&D waste can reduce the adverse environmental impacts of construction activities, as well as promote economic activities across the industry (EPA, 2019b).

Despite pressing attention on C&D waste issues from both academics and practitioners, low R&R quantities of C&D waste is still pointed out as a limitation of construction projects (CIB, 2014; Tam, 2011; UNEP and ISWA, 2015; Won and Cheng, 2017). An example is concrete waste recycling in the United States – it is estimated that only 50% of the material is recycled (CIB, 2014). For some countries, including the

United States, the development of a construction waste management plan (CWMP) is a legislative requirement that intends to maximize the diversion of CW from landfills (EPA, 2007). A CWMP typically includes estimates of CW quantities for R&R, on-site CW storage area, methods for CW sorting and reduction, and stakeholders responsible for waste disposal (McGrath, 2001; Tam, 2008). While the benefits of a CWMP are recognized, its implementation is challenged by the perception of productivity loss and delay of other activities with higher priority in the project (Tam, 2008). As such, there is a need to improve the efficiency of CWM planning at the project level without affecting different project objectives (e.g., meeting budget, schedule, and safety standards).

Building Information Modeling (BIM) is endorsed as a major development for the Architectural, Engineering, and Construction (AEC) industry (Eastman et al., 2011). Over the last decade, BIM has gained popularity, and CWM is a domain with increasing BIM applications; examples include waste reduction (Liu et al. 2015), automated CW estimation (Guerra et al. 2019), and disposal planning (Cheng and Ma, 2013). Notably, parametric modeling, visualization, and simulation capabilities of BIM offer an opportunity to improve the efficiency of CWM planning. However, a comprehensive review of stakeholders' needs on BIM for CWM reveals that there is *still* an expectation for computer-aided tools that enable *visualization* of CW performance throughout different phases of the building lifecycle (Akinade et al., 2018). Furthermore, a review of existing BIM-based applications for CWM, reveals the lack of an approach that is able to discretize CW generation in quantities for on-site reuse and off-site recycling, without relying on external factors, and pinpointing specific activities in the construction schedule able to admit reuse of CW.

In this context, the study presented in this chapter leverages four-dimensional (4D) BIM to enhance CW R&R planning at the project level addressing the aforementioned limitations (i.e., discretizing amounts of CW for on-site reuse and off-site recycling, without relying on fixed waste factors or regional data, and visually indicating specific activities in the schedule able to admit reuse of CW). By integrating the temporal dimension to BIM, CW generation can be visualized as construction activities are performed, therefore facilitating the planning of CW reuse on-site, and CW recycling off-site. Concrete and drywall waste streams from two nonresidential case studies in Central Texas are used to demonstrate the application of 4D-BIM for R&R planning. The above-mentioned waste streams were selected as they are consistently among the three largest CW streams produced in the United States (EPA, 2015; 2016; 2018; 2019a). Moreover, concrete has a high potential for both R&R, while drywall in good condition has potential for recycling.

Proactively and efficiently planning for CW R&R enables maximizing resource recovery by down-cycling and up-cycling waste streams, ultimately reducing the amounts of CW directed to landfills. The overarching objective of this chapter is to streamline CW R&R planning at the project level, by proposing a visual and temporal approach based on data commonly available in construction projects (i.e., BIM, construction schedule, and purchasing records), and thus applicable to different types of projects independent of geographic location. Specific contributions of this chapter include: (1) providing a method for the visual identification of construction activities able to admit CW for on-site reuse, thus enabling more effective and formal planning; (2) relying on BIM to estimate CW quantities for R&R to avoid manual and lengthy estimations; and (3) validating CW R&R estimates of two case studies with real-world data (i.e., ground truth data from waste hauling tickets), and literature values using two different approaches (i.e., percentage of material wasted, and waste generation rates). In summary, the culmination of this chapter provides a computer-aided approach to visualize and plan for the generation of two major waste streams during the construction phase of the project – thus, aligned with one major expectation of stakeholders' towards BIM for CWM (Akinade et al., 2018). The application of the proposed approach aligns with the United States Environmental and Protection Agency's aim to develop better national recovery estimates for building constructions (EPA, 2009b).

3.2 Background Research

BIM is defined as the "digital representation of the physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception onward" (NBIMS, 2015, Chapter 3., p. 3). Different levels of development (LOD) specifies minimum content requirements and uses of the BIM, the LOD varies progressively from 100 (i.e., least developed) to 500 (i.e., most developed) (AIA, 2013). Furthermore, such digital representation can be multi-dimensional (i.e., nD), in which each dimension describes a different hierarchy of information required at different stages of the facility's lifecycle (GhaffarianHoseini et al., 2017; Lee et al., 2005). A systematic review of all dimensions of BIM and its applications throughout different stages of the project's lifecycle is provided by Charaf et al. (2018) – in general, the most common dimensions beyond 3D are understood as 4D (scheduling), 5D (cost estimating), 6D (sustainability), and 7D (facility management). The approach proposed in this chapter focuses specifically on the fourth-dimension of BIM (4D-BIM), which consists of the linkage of temporal information (i.e., construction schedule) to the 3D model (Kacprzyk and Kepa, 2014). Project planning and sequencing (Choi et al, 2014; Charaf et al., 2018), safety analysis (Choe and Leite, 2017; Zhang et al., 2015), and progress monitoring (Braun et al., 2014; Han and Golparvar-Fard, 2014) are examples of widespread uses of 4D-BIM in the AEC industry. Section 3.2.1 provides an overview of the 3R's waste management principle – i.e., reduction as the most desired option in the hierarchy, followed by reuse, and recycling – and how BIM has been employed to improve CW reduction, reuse, and recycling. Section 3.2.2 synthesizes specifically 4D-BIM applications for CWM available in the literature. Lastly, Section 3.2.3 provides an overview of concrete and drywall waste R&R.

3.2.1 3R's Waste Management Principle and BIM

Reduction is pointed out as the best solution as it minimizes the C&D waste generation (Peng et al., 1997; Poon, 2007). According to Lu and Yuan (2011) waste reduction strategies can be summarized in five categories: (1) waste reduction through government legislation; (2) development of an effective waste management system; (3)

use of low waste technologies (e.g., pre-fabrication, steel formwork); (4) improvement in practitioners' attitudes toward waste reduction; and lastly, (5) waste reduction through design. Of these five categories, strategies for CW reduction during the design phase of a project have largely been the focus in literature. This is likely due to the close relationship between CW generation and decisions made early in the project – it is estimated that about one-third of CW could arise from poor design decisions (Osmani et al. 2008). Notably, the potential of BIM for CW reduction through design has been explored by different researchers. Porwal and Hewage (2012) investigated the reduction of rebar trim waste by using an optimization algorithm with a structural BIM model; Liu et al. (2015) developed a decision-making framework for improving CW minimization; Salgin et al. (2017) examined the potential of BIM applications in preventing and reducing CW; Won et al. (2016) estimated the CW prevented by BIM-based design validation using case studies in South Korea; Lu et al. (2017) developed a prototypical framework in which architects and designers can automatically calculate the quantities of CW generation for a given design option and construction scheme; Cheng et al. (2015) investigated the potential of BIM for supporting CWM during building design; and Akinade et al. (2016) evaluated the performance of existing CWM tools and employed the results in the development of a BIM framework that aims design for CW minimization.

When CW reduction is not possible, reuse is the next option in the 3R's hierarchy (Tam, 2011). Reuse of CW refers to utilizing materials more than once for the same purpose or utilizing materials for a purpose different than the one initially proposed. For instance, wood reuse for formwork used in different structural elements (Bakchan et al., 2019a); or reuse of concrete waste as general fill (U.S. Army Corps of Engineers, 2004). Reuse is a desirable option due to the minimum processing and energy use required (Peng et al., 1997); yet, when compared to other research domains such as CW reduction and recycling, reuse has received less attention (Lu and Yuan, 2011). Traditionally, when it comes to reuse, much focus is given to the waste generated from the demolition phase of the project; specifically, extensive research is available with regards to building deconstruction and related BIM-based optimization. Examples include: Diyamandoglu and Fortuna (2015) who analyzed the viability of wood framed houses deconstruction in regard to reduction of greenhouse gas emissions and energy savings of recovering the reusable materials to resale; Queheille et al. (2019) who proposed a multi-objective optimization model for building deconstruction; Akinade et al. (2015a) who developed a BIM-based deconstructability assessment score to determine the extent to which a building could be deconstructed right from its design stage; Akbarnezhad et al. (2014) who proposed a framework to evaluate and compare the effects of various alternative deconstruction strategies on cost, energy use and carbon footprint using data provided by BIM models; Iacovidou et al. (2018) who analyzed the potential of Radio Frequency Identification (RFID) coupled with BIM for tracking structural components that could be potentially reused after deconstruction; and Akanbi et al. (2018), who developed a BIM-based tool to forecast the whole-life salvage performance of buildings still from the design stage. However, little research focuses on the use of BIM for reuse of waste generated during construction activities; this is the case of Hewage and Porwal (2011) and Bakchan et al. (2019b), which are discussed in Section 3.2.2.

Recycling is the last option in the 3R's waste management principle due to the energy required and side streams (i.e., waste) produced (Bartl, 2014). Despite being in the third position of the waste management hierarchy, recycling exhibits a predominant role and is one of the major topics in the discipline of C&D waste management (Bartl, 2014; Lu and Yuan, 2011). Recycling is the reprocessing of recovered materials at the end of a product's life, returning the materials to the supply chain (Worrel and Reuter, 2014). According to Edwards (1999) benefits of recycling include: (1) reduction of demand of new resources; (2) reduction of transport and production energy costs; and (3) use of waste which would be landfilled. Typical barriers to recycling include an increase in management and recycling operation cost, lack of legislation control, lack of incentive, and limited facilities options (Oyenuga, 2014; Crawford et al., 2017). The viability of recycling facilities in different countries is a topic with large attention within the recycling domain – Duran et al. (2006) developed a model to analyze the economic viability of recycled C&D waste in Ireland; Coelho and Brito (2013) studied the economic viability of the implementation of a large-scale, high-end, recycling plant to serve an urban area of Portugal; Zhao et al. (2010) evaluated the economic viability of C&D waste recycling facilities in Chongqing, in China, revealing still a large demand for recycled materials; and Nunes et al. (2007) collected and analyzed data about C&D recycling waste in Brazil and developed a model to analyze viability of future recycling facilities. Properties of recycled materials is another topic with large attention within the recycling domain – Tam and Tam (2006) reviewed the technology and feasibility of recycling ten major construction waste streams; Silva et al. (2014) performed a thorough literature review to examine the factors affecting the compositional properties (e.g., physical, chemical, mechanical) of C&D recycled aggregates intended for concrete production; and Cardoso et al. (2016) conducted an extensive literature review on the physical properties of different types of recycled aggregates and compared it with natural aggregates to evaluate how these differences affected the performance in geotechnical applications. In summary, BIM applications for CW reduction is a topic largely discussed in the literature, especially during the project's design phase. With regards to reuse, much attention is directed at the waste generated during the demolition phase, as well as different BIM applications for deconstruction. On the other hand, few BIM applications are devoted to on-site CW reuse planning during construction. Recycling is a major topic in the CWM domain, nonetheless, to the best of the authors' knowledge, few studies focus on BIM's potential for supporting CW recycling estimation and planning.

3.2.2 4D-BIM and CWM

4D-BIM has been receiving increasing attention for CWM purposes in the past years (Jupp, 2017). Different authors discussed the use of 4D-BIM for CW reduction (Cheng et al., 2015; Bortolini et al., 2019), while others proposed 4D-BIM applications for CWM. Hewage and Porwal (2011) proposed a 4D-BIM system dynamics model capable of predicting material waste and indicating possibilities of reuse in construction. However, one limitation of this study, is that it focuses solely on waste caused by rework activities, and not in CW generation throughout the project's construction phase. Bakchan et al. (2019b) proposed a theoretical BIM framework for CWM which suggests the use of 4D-BIM for CW disposal planning and scheduling. While the study is comprehensive and also suggests CW reuse on-site planning, it falls short in the planning and estimation of CW quantities for off-site recycling, which is necessary for a more detailed CWMP. Won and Cheng (2017) developed a 4D-BIM CW estimation framework. Nonetheless, the authors rely on CW factors for the estimation of waste generation – an approach that may not be suitable for different types of construction or different geographical locations. Additionally, the proposed framework lacks identification of specific activities in the schedule for CW reuse, which difficult planning at the site level. In summary, the limitations of existing 4D-BIM applications for CWM are: (1) focus solely on CW generated by rework activities (Hewage and Porwal, 2011); (2) lack of estimation of CW for off-site recycling (Bakchan et al., 2019b); and (3) use of fixed factors for the estimate of CW, and lack of identification of activities in the schedule for CW reuse (Won and Cheng, 2017).

3.2.3 Concrete and Drywall Waste Reuse and Recycling

Concrete is a material with high potential for R&R (U.S. Army Corps of Engineers; 2004). Hardened leftover amounts of concrete waste can be reused on-site as clean fill (DEP, 2019; Tam and Tam, 2006), a practice that is common to backfill and level up open areas to necessary grades (EPA, 2018). Besides on-site waste reuse, concrete is a material with high potential for off-site recycling. In this case, the concrete waste is directed to recycling facilities where the material is crushed, reinforcement bars are removed, and recycled concrete aggregates (RCA) are produced. RCA can be used for different purposes, such as: (1) aggregates for new structural concrete (Oikonomou, 2005; Wagih et al., 2013); (2) general fill (EPA, 2009a; U.S. Army Corps of Engineers, 2004); (3) road base material (Oikonomou, 2005; EPA, 2009a); (4) soil stabilization material (Oikonomou, 2005; U.S. Army Corps of Engineers, 2004); and (5) pavement for trails (U.S. Army Corps of Engineers, 2004). As stated in Section 3.2.1, the properties of recycled materials is a topic with large attention in the literature. Due to the significant representation of concrete in overall C&D waste generation, several studies focus on the use of RCA to replace natural coarse aggregate in concrete production (Wagih et al., 2013; Poon and Chan, 2006). Benefits of this practice includes reducing the environmental burden, and alleviating the demand for landfill space (Poon and Chan, 2006; U.S. Army Corps of Engineers, 2004).

Drywall waste from demolition and renovation projects are usually not suitable for recycling due to the presence of contaminants – e.g., nails, tape, paint, wallpapers, joint compound – which further challenges the recycling process (Ndukwe and Yuan, 2016; Pichtel, 2014). Nonetheless, drywall waste from new construction is a material with high potential for recycling due to the low levels of contaminants (CDRA, 2019; Marvin, 2000). Different applications are available for uncontaminated scrap gypsum drywall waste, potential uses are: (1) new drywall remanufacture (Marvin, 2000; CIB, 2014; CDRA, 2019); (2) ingredient for Portland cement production (Pichtel, 2014; CIB, 2014; CDRA, 2019); (3) soil amendment products (e.g., general agriculture, mushroom culture, nurseries) (Pichtel, 2014; Marvin, 2000; CIB, 2014, CDRA, 2019); and (4) animal bedding (Marvin, 2000). Recycling drywall waste alleviates landfill disposal problems, which are especially challenging for this waste stream due to its anaerobically decomposition which produces high levels of flammable and hazardous gas (i.e., hydrogen sulfide) (Ndukwe and Yuan, 2016; Marvin, 2000). In the context of reuse, unlike the concrete waste stream, gypsum drywall waste on-site reuse is not common due to the careful handling and systemic removal approach required. Nonetheless, donation of discarded drywall sheets either in half or larger sizes to nonprofit organizations that build affordable housing is a common practice (Austin Habitat for Humanity, 2020).

3.3 Research Approach

The following sub-sections present the algorithms developed for concrete and drywall waste R&R estimate. The case studies used to demonstrate these algorithms, and an illustration of 4D-BIM for CW R&R planning are presented as follows.

3.3.1 Construction Waste Generation Estimation

Construction is a physical process, therefore it follows the mass balance principle – that is, materials used for construction activities either become waste or accumulate in the built elements (Himmelblau, 1996). A CW generation estimation method based on the mass balance principle, and automated using BIM-based quantity takeoff (QTO), is used in this approach (Guerra et al., 2019). As such, CW generation is considered as the portion of materials purchased, reduced by the portion of materials needed in the structure – which are retrieved from BIM (Eqn. 3-1). Still, caution is required when utilizing BIM as a major source of project quantities. In such cases, accuracy between the model and the construction plans utilized on-site are fundamental to guarantee that the automated QTO is accurate and will lead to reliable estimates. A minimum LOD 300 is expected for the model in order to enable assembly-based QTO's and scheduling tasks (Latiffi et al., 2015). Additional model requirements, specifically related to concrete and drywall 3D elements' properties are described in Appendix B. Notably, the CW generation estimation is not performed only once for the entire construction project, but rather based on sequential sections of building construction as determined in the schedule (i.e., in Eqn. 3-1, Section A is the initial section of building construction, which will be followed by the construction of Section B); as such, integrating the fourth dimension, time, into the estimates. This is due to the availability of materials' purchasing records for each construction section, and to enable a more effective identification of activities suitable for CW reuse as construction progresses. The CW generation estimate for the entire project is a summary of the CW generation estimated for each construction section (i.e., Section A plus Section B, and all subsequent sections in the construction schedule).

$$CW_{\text{Estimated, Section } A} = \sum_{\text{Purchased, Section } A} - \sum_{\text{Needed, Section } A} \qquad \textit{(Eqn. 3-1)}$$

To promote a detailed CWMP, the presented approach seeks to discretize the amounts of CW generation that are directed for on-site reuse, off-site recycling, and landfilling. Therefore, the backbone of the proposed approach is demonstrated in Eqn. 3-2, in which the CW generation estimate for the entire project is reduced by the total amount of CW reused on-site and the total amount of CW to be recycled off-site, resulting in the amount of CW directed to landfills.

$$CW_{\sum Estimated} - CW_{\sum Reused} - CW_{\sum Recycled} = CW_{Landfilled} \qquad \textit{(Eqn. 3-2)}$$

3.3.2 Description of Case Studies

Two nonresidential case studies from Central Texas were selected to demonstrate the application of the algorithms. Case Study A is an institutional building of 40,135 m^2 which includes open and flexible learning spaces, faculty and students' offices, classrooms, laboratories, a library, and an auditorium. The building has eight levels (i.e., mid-rise building) of which the first three are integrated and the remaining five levels are separated into two towers. One particularity of this project's architecture is the creation of a confined atrium in the middle of the building due to a sunshade structure on the eight-story. Case Study B is a mixed-use tower of 19-stories (i.e., high-rise building) that includes two floors of amenities, eight floors of parking spaces, and nine floors of office spaces – totaling 30,658 m^2 of build-up area. Both buildings' superstructure are composed of reinforced cast-in-place concrete, the buildings' façades are composed of concrete masonry units (CMU) and curtain wall systems, and the interior walls are made of steel frame and drywall. These characteristics are common to mid and high-rise building construction in larger cities in Texas (Assanie and Weiss, 2019; Sarac, 2019;

Widner, 2020). Both projects have the same owner but were built by different general contractors. As such, we can expect different purchasing strategies, and on-site practices. Additionally, since 2008, the owner of the projects requires that all new construction participate in the United States Green Building Council (USGBC) Leadership in Energy and Environment Design (LEED) program – a popular voluntary certification scheme that is reference in the development of sustainable buildings (Pulselli et al., 2007; Wu et al., 2016). Case Study A and B were strategically selected due to the availability of: (1) structural BIM containing concrete elements; (2) architectural BIM containing drywall partitions; (3) general contractor's purchasing records; (4) as-built construction schedule; (5) CWMP stating expected CW reuse and recycling rates; (6) truckload hauling tickets documenting actual CW generation and recycling quantities; and (7) LEED certification documentation.

3.3.3 Concrete Waste Reuse and Recycle Estimation

Figure 3-1 demonstrates the application of the proposed algorithms for the concrete waste stream. For this approach, concrete waste generated during construction is primarily reused in subsequent activities that will require clean fill material; out of the remaining waste, part is sent to off-site recycling facilities, and the leftovers are sent to landfills.

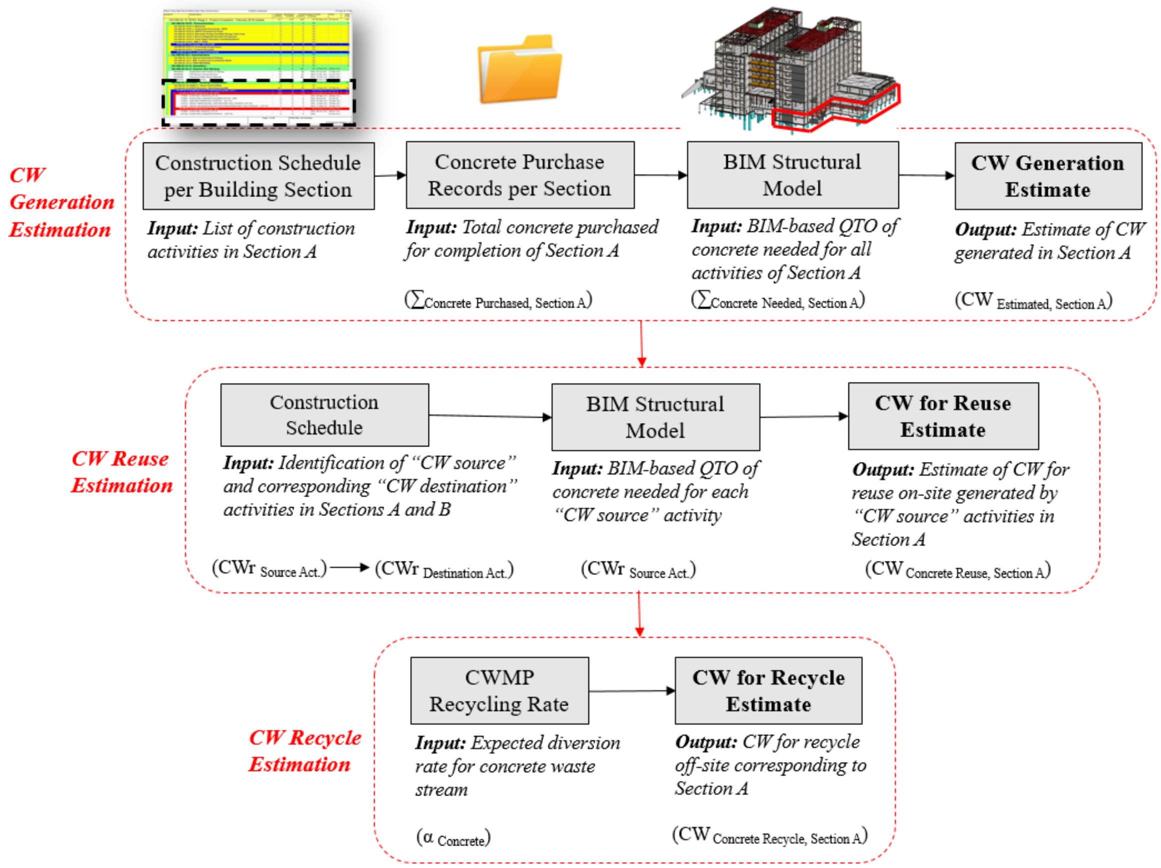


Figure 3-1: Concrete Waste: Generation, Reuse, and Recycle Estimation

The initial step is to estimate the concrete waste generation of the first section of the building construction (i.e., Section A), using Eqn. 3-1. Based on the construction schedule, the next step is to identify activities that require clean fill material (i.e., concrete waste) on the subsequent section of the building construction (i.e., Section B). Activities requiring clean fill are referred to as $CWr_{\text{Destination Act.}}$. Using a backwards approach, concrete pours executed in Section A are identified and analyzed, these activities (referred to as $CWr_{\text{Source Act.}}$) are the ones potentially generating concrete waste for reuse on-site during the construction of Section B. Notably, not every concrete pour executed in Section A is considered a $CWr_{\text{Source Act.}}$, for instance, cast-in-place concrete piles are activities in which concrete waste tends to be lost on-site and thus is not suitable for reuse. Additionally, a time frame of one month is integrated between an activity that requires concrete waste for reuse (i.e., $CWr_{\text{Destination Act.}i}$) and its corresponding concrete pour activity (i.e., $CWr_{\text{Source Act. }i}$); this is due to logistics considerations and feasibility of waste storage on-site, which can pose a challenge to CW reuse (Crawford et al. 2017).

The estimate of total concrete waste for reuse on-site, generated by $CWr_{\text{Source Act.}}$ activities of Section A, is performed using Eqn. 3-3. From Eqn. 3-3, the volume of concrete needed for each $CWr_{\text{Source Act.}}$ is divided by the volume of concrete needed for all activities in Section A ($\sum_{\text{Concrete Needed, Section A}}$), and multiplied by the concrete waste estimated for Section A ($CW_{\text{Concrete Estimated, Section A}}$ - Eqn. 3-1). Notably, the volume of concrete needed for these activities is leveraged automatically from the structural BIM.

$$CW_{\text{Concrete Reuse, Section A}} = \left(\frac{\sum \text{CWr Source Act.}}{\sum \text{Concrete needed Section A}} \right) * CW_{\text{Concrete Estimated, Section A}}$$

(Eqn. 3-3)

The amount of concrete waste potentially recycled off-site, corresponding to the construction of Section A (Eqn. 3-4), is equal to the total amount of concrete waste estimated for Section A ($CW_{\text{Concrete Estimated, Section A}}$ - Eqn. 3-1) reduced by the amount of concrete waste for reuse on-site ($CW_{\text{Concrete Reuse, Section A}}$ - Eqn. 3-3), and multiplied by the expected diversion rate of the concrete waste stream (α_{Concrete}, in percentage). The expected diversion rate of the concrete waste stream is stated in the project's CWMP; this expected rate is usually based on past projects' performance, or on CWM goals of the project. The abovementioned estimates (i.e., CW generation, CW for reuse, and CW for recycling) are to be performed for each building section to determine the estimates for the entire construction.

$$CW_{\text{Concrete Recycle, Section A}} = (CW_{\text{Concrete Estimated, Section A}} - CW_{\text{Concrete Reuse, Section A}}) * \alpha_{\text{Concrete}}$$

(Eqn. 3-4)

3.3.4 Drywall Waste Recycle Estimation

Due to the impracticality of drywall waste reuse on-site, only the waste generation and off-site recycling amounts are estimated for the drywall waste stream – as demonstrated in Figure 3-2. Similarly to the concrete waste stream, estimates of drywall waste generation and off-site recycling quantities are performed based on the sequential sections of building construction determined in the schedule.

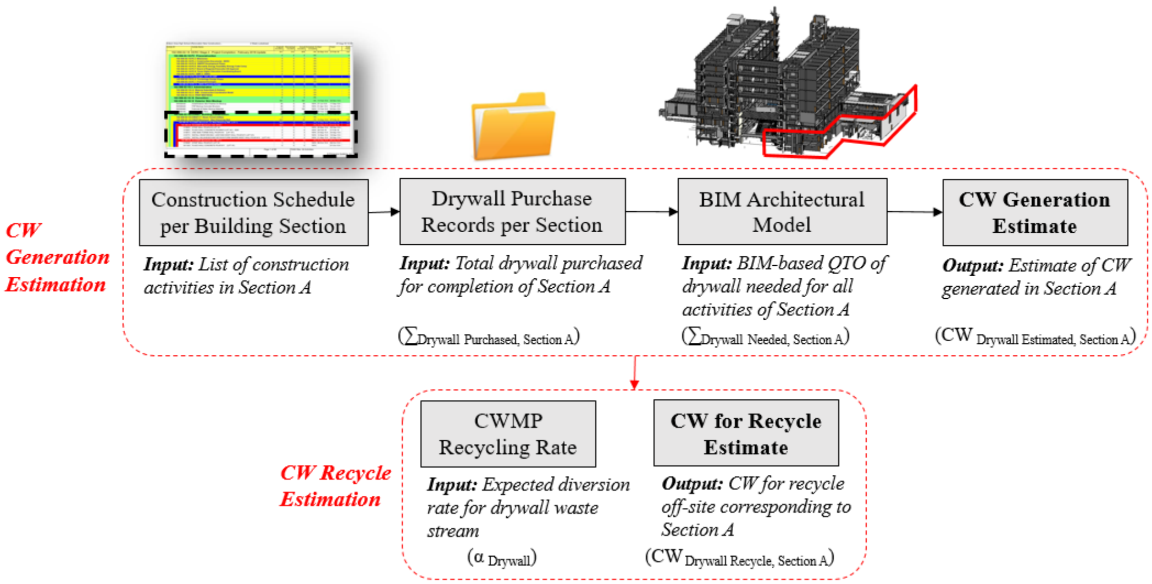


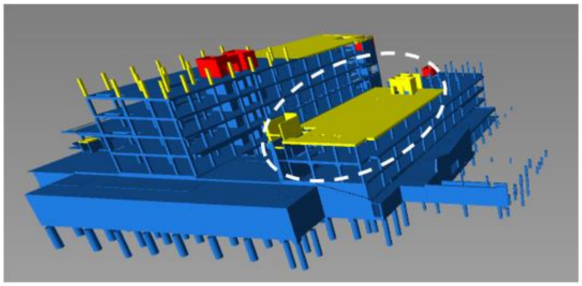
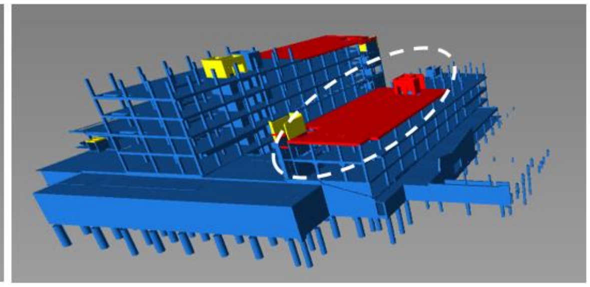
Figure 3-2: Drywall Waste: Generation and Recycle Estimation

For the estimation of drywall waste, it is assumed that all materials reported as purchased for each building section, for instance, Section A ($\sum_{\text{Drywall Purchased, Section }A}$ – Eqn. 3-1), by the general contractor, are materials acquired for the specific project to which CW estimation is being performed. Such consideration assures that the waste estimated is due to rework and cutouts. The amount of drywall potentially recycled off-site, generated from the construction of Section A (Eqn. 3-5), is the amount of drywall waste estimated for the entire section ($CW_{\text{Drywall Estimated, Section A}}$ – Eqn. 3-1) multiplied by the expected diversion rate of the drywall waste stream, stated in the project's CWMP (α_{Drywall}, in percentage).

$$CW_{\text{Drywall Recycled, Section A}} = CW_{\text{Drywall Estimated, Section A}} * \alpha_{\text{Drywall}} \qquad \textit{(Eqn. 3-5)}$$

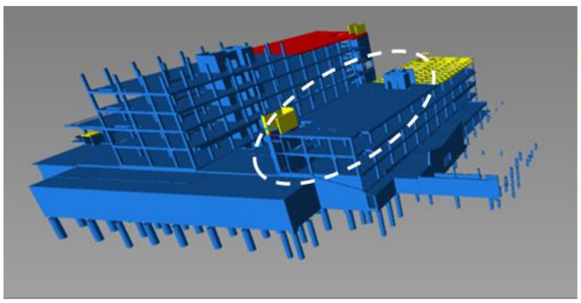
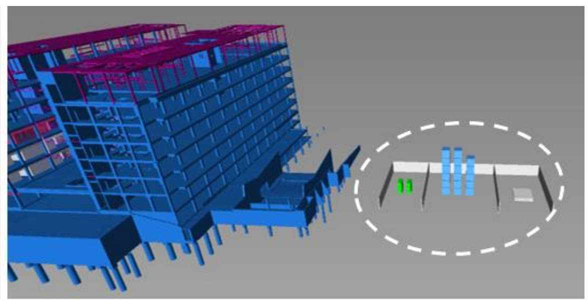
3.4 4D-BIM FOR CW R&R PLANNING VISUAL DEMONSTRATION

4D-BIM's were developed during the pre-construction phase of both case studies. For Case Study A, a 4D simulation was developed with the objectives of: (1) confirming clearances and simulating the installation of a large piece of stainless steel in the building; and (2) simulating access of large construction equipment (i.e., crane) in the building's confined atrium. For Case Study B, a 4D simulation was developed with the objective of validating the construction sequence proposed in the schedule. In summary, 4D-BIM was not used for CWM planning purposes in either case study, therefore, separate 4D simulations were developed to visually demonstrate the application of the proposed algorithms. Figures 3-3 and 3-4 illustrate the simulation of Case Study A. All information pertaining to the construction schedule, structural BIM, and architectural BIM that were not related to concrete or drywall waste generation was disregarded (e.g., mechanical, electrical and plumbing components and activities). In this 4D-BIM, each 3D element of the building appears in the simulation with a different color, based on the construction activities performed (Figure 3-3). The piles demonstrating CW generation (Figure 3-3 D) are separated according to the waste stream produced and disposal method (i.e., concrete waste for on-site reuse, concrete waste for off-site recycling, and drywall waste for off-site recycling).

A – Formwork placement (yellow) of South Tower 3rd floor slab

B – Steel placement (red) of 3rd floor slab

C – Concrete placement (blue) of 3rd floor slab

D – CW generation

Figure 3-3: 4D-BIM for CW R&R simulation

Each CW block for off-site recycling appears on the simulation when 15.4 m^3 of the corresponding waste stream is accumulated. This frequency was set up intentionally due to the average capacity of the waste bins used in Case Study A, and with the purpose of aiding visual planning of CW removal dates. Concrete waste for on-site reuse blocks appears on the simulation once a $CWr_{\text{Source Act.}}$ activity is finalized. This waste is then directed to a stockpile and later will be reused as clean fill in its corresponding $CWr_{\text{Destination Act.}}$ activity (Figure 3-4). Refer to Appendix D for guidelines on how to develop the 4D simulation.

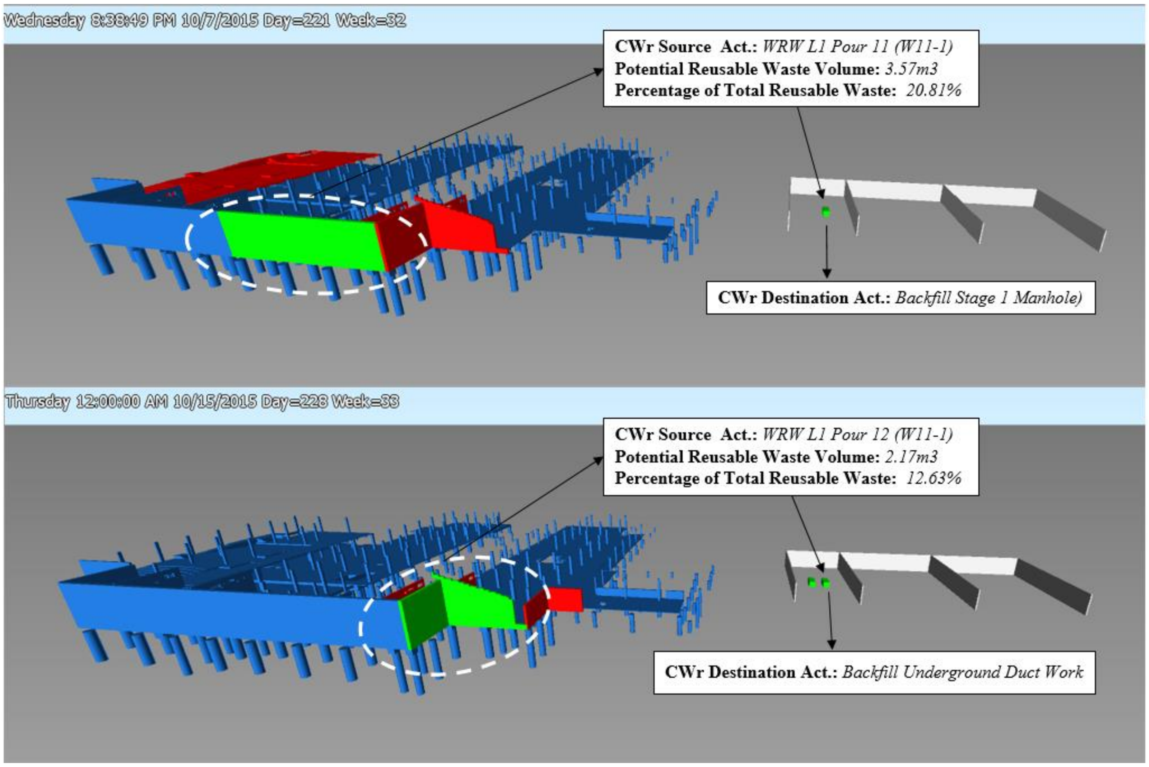


Figure 3-4: Concrete waste reuse sequence demonstration in Case Study A

3.5 Estimation Results

Table 3-1 demonstrates the overall estimate of concrete and drywall waste generation for the case studies. The amounts of concrete and drywall purchased for these projects was retrieved from each corresponding general contractor's purchasing records. The total amount of concrete needed for all structural elements of the projects (i.e., slabs, piles, columns, beams, and stairs), and the total amount of drywall needed for all interior walls of the projects, was leveraged through automated QTO from each corresponding BIM. Notably, the structural elements were discounted a steel reinforcement (i.e., rebar) volume according to its category (1.5% for slabs, 2% for piles, columns, beams, and stairs – as proposed and demonstrated in Guerra et al., 2019). On the other hand, the drywall quantities did not include further deductions as the amounts retrieved from BIM already discount openings such as doors and windows.

Case Study	Waste Stream and Unit	Material Purchased (∑ Purchased)	Material Needed (∑ Needed)	Estimated Waste (CW ∑ Estimated)
A	Concrete (m^3)	14,555.0	14,242.8	312.2
B	Concrete (m^3)	19,028.0	18,642.5	385.5
A	Drywall (m^2)	111,112.0	95,797.8	15,314.2
B	Drywall (m^2)	99,824.8	89,598.5	10,226.3

Table 3-1: Concrete and drywall waste generation estimates

The construction schedule of each case study was individually analyzed to identify concrete waste reuse opportunities (i.e., activities requiring clean fill material). For Case Study A, a total of 24 activities were identified as requiring clean fill material – the majority of activities identified were underground utilities and backfill of retaining walls. For Case Study B, only one retaining wall (divided into three concrete pours) in the north face of the underground level was identified as requiring backfill. This information was confirmed by the project engineer of Case Study B, who affirmed that the project utilized a temporary soil retention system for other retaining walls of the underground level. Accordingly, the concrete pours that were executed one month earlier than the activities requiring clean fill material were identified. A total of 10 pairs of waste reuse source activities ($CWr_{Source\ Act.}$) and destination activities ($CWr_{Destination\ Act.}$) were identified that met the one-month time constraint in Case Study A (see Table 3-2). For

Case Study B, five concrete pours were executed in the month prior to the backfilling of the north face retaining wall. However, out of these activities, only four were selected as $CWr_{\text{Source Act.}}$ (see Table 3-3) because one of the activities identified was the concrete pour of piles, which makes the separation of waste for reuse difficult. Tables 3-2 and 3-3 demonstrate the estimates of concrete waste for reuse generated by the source activities identified.

Concrete Waste Reuse Destination Activity Description ($CWr_{\text{Destination Act.}}$)	Concrete Waste Reuse Source Activity Description ($CWr_{\text{Source Act.}}$)	Concrete needed for ($CWr_{\text{Source Act.}}$) in m^3	Estimated Concrete Waste for Reuse (CW_{Reuse}) in m^3
• Backfill Stage 1 Manhole	• WRW L1 Pour 11 (W11-1)	162.9	3.6
• Backfill Underground Duct Work	• WRW L1 Pour 12 (W12-1)	98.9	2.2
• Backfill at New Manhole	• South Elevator Walls L1-2 Pour	43.7	1.0
• Backfill Underground Utilities at Auditorium	• North Grade Beam at North Auditorium Wall Pour	12.6	0.3
• Complete Backfill SOG 3.4 South Tower	• Columns Area 4A L0-1 Atrium Pour	5.5	0.1
• Gravel Backfill/Flow fill at NW Corner Area A	• South Auditorium Wall 18 Pour	188.8	4.2
• Backfill 4" and 8" Waste Water Lines from Stage 1 Connection to Building East of Auditorium	• Grade Beams at Area A Courtyard Pour	24.9	0.6

Table 3-2: Estimate of concrete waste for reuse on-site (Case Study A)

• Backfill Exterior Walls at Auditorium	• Stair F Pour	163.2	3.6
• Backfill/Fine Grade at Grade Beam/SOG at NW Corner Area A	• Grade Beams at SOG North West Corner Area A Pour	46.6	1.0
• Partial Backfill at Buttress Planter Walls South of Auditorium	• Strip Base at Fire Lane South of Auditorium Pour	35.8	0.8
		Total Concrete for Reuse ($CW_{\sum Reused}$)	17.4

Table 3-2, continued: Estimate of concrete waste for reuse on-site (Case Study A)

Concrete Waste Reuse Destination Activity Description ($CWr_{Destination\ Act.}$)	Concrete Waste Reuse Source Activity Description ($CWr_{Source\ Act.}$)	Concrete needed for ($CWr_{Source\ Act.}$) in m^3	Estimated Concrete Waste for Reuse (CW_{Reuse}) in m^3
• Backfill Underground North Retaining Wall – Section 1	• Form, rebar, pour Slab-on-Grade – Pour 1	151.0	3.1
• Backfill Underground North Retaining Wall – Section 2	• Form, rebar, pour Slab-on-Grade – Pour 2	196.5	4.1
• Backfill Underground North Retaining Wall – Section 3	• Form, rebar, pour Columns Basement Level – Pour 1	77.8	1.6
• Backfill Underground North Retaining Wall – Section 3	Form, rebar, pour Columns Basement Level – Pour 2	81.0	1.7
		Total Concrete for Reuse ($CW_{\sum Reused}$)	10.5

Table 3-3: Estimate of concrete waste for reuse on-site (Case Study B)

The CWMP of both case studies were analyzed to review the projects' performance requirements and expected diversion rates for concrete and drywall waste streams. Both case studies sought LEED Silver certification – which is the second to lowest tier in the LEED certification scheme (i.e., Certified, Silver, Gold, and Platinum); the CWMP of the projects also stated a minimum diversion rate of 75% for at least four different waste streams. Concrete was one of the waste streams specified in the CWMP to be diverted to recycling facilities; therefore, the expected diversion rate (α Concrete) used to estimate the amount of concrete waste for off-site recycling is 75%. On the other hand, drywall was not a waste stream diverted from landfills in either case study; lack of recycling facilities able to process this waste stream near both project locations deemed recycling unfeasible. This barrier is confirmed by a recent study on the economic impacts of recycling in Texas, which shows strong and growing recycling activity in the Dallas-Fort Worth and Houston regions, but slow and weak recycling activities in other parts of the State (Burns and McDonnell, 2017). As such, the estimate of drywall for recycling is performed based on a "what-if" scenario, assuming the presence of nearby recycling facilities able to process this waste stream. An expected diversion rate (α Drywall) of 28% is used based on the International Council for Research and Innovation in Building and Construction (CIB) (2014) estimate of annual drywall recycling in the U.S. The total amount of concrete and drywall waste for off-site recycling is demonstrated in Table 3-4.

Case Study	Waste Stream and Unit	Waste Generation ($CW_{\sum Estimated}$)	Waste for Reuse ($CW_{\sum Reused}$)	Recycling Rate (%)	Waste for Recycling ($CW_{\sum Recycled}$)
A	Concrete (m^3)	312.2	17.4	75	221.1
B	Concrete (m^3)	385.5	10.5	75	281.3
A	Drywall (m^2)	15,314.2	-	28	4,287.0
B	Drywall (m^2)	10,226.3	-	28	2,863.4

Table 3-4: Concrete and drywall waste recycling estimates

3.6 Estimations Validation and Discussions

The total concrete waste estimated for Case Study A is 312.2 m^3 (725.2 tons – using the concrete density of 2,322.7 kg/m^3; ACI Committee 318, 2014), and for Case Study B is 385.5 m^3 (895.4 tons). These estimates were validated with actual waste generation cataloged in the waste hauling tickets of the case studies. For Case Study A, the difference between the concrete waste estimated (725.2 tons) and the actual waste generation (652.9 tons – Guerra et al, 2019) is 11.1%. For Case Study B, the difference between the waste estimated (895.4 tons) and the actual waste generation (1,074.9 tons) is 16.7%. Different factors may have caused variations between the concrete waste estimates and the actual waste catalogued in the hauling tickets of both case studies, some possibilities are: (1) different purchasing strategies from the companies; (2) different concrete density used to perform estimates; (3) variations between the structural BIM and construction plans used on-site; (4) rework activities or modifications not accounted for in the schedule of the projects; and (5) concrete waste not accounted for or catalogued in the hauling tickets (e.g., over-pouring in uneven surfaces, differences between exact formwork location and its designed position, loss during material transportation). Nevertheless, concrete waste estimates of both case studies fall in accordance with results of different authors, such as Li et al. (2013) which report a difference of up to 20% between actual waste generation and estimated, and Kazaz et al. (2015) which report a waste of 1% to 13.2% of the amount of concrete purchased depending on the geographic location. Furthermore, the waste generation rate (WGR) – a popular metric of waste generation expressed in kg/m^2 (Wu et al., 2014) – of the concrete waste stream of both case studies is 18.1 kg/m^2 and 29.2 kg/m^2, respectively. These numbers falls in accordance with estimates of Cochran et al. (2007b) for nonresidential building construction in the U.S. – up to 33 kg/m^2.

The total drywall waste estimated for Case Study A is 15,314.2 m^2 (183.77 tons – using an average weight of 12 kg/m^2; Gypsum Association, 2017), whereas for Case Study B is 10,226.3 m^2 (122.7 tons). On-site sorting of drywall waste for recycling was not performed in either case study (i.e., drywall waste was catalogued commingled with trash in the waste hauling tickets), therefore, validating the estimates with actual quantities was not possible. As such, the estimates of drywall waste generation are validated based on studies of nonresidential buildings in North America. For Case Study A, it is estimated that 13.8% of the material purchased was wasted during installation; for Case Study B this number is 11.4%. According to Cochran and Townsend (2010), Michigan (2007), Pichtel (2014), and Ndukwe and Yuan (2016), approximately 12% of drywall material is wasted during installation. Furthermore, the WGR of drywall for each case study is 4.6 kg/m^2 and 4.0 kg/m^2, respectively; numbers that are in accordance with rates reported by Cochran et al. (2007b) – up to 5.2 kg/m^2.

LEED Silver is the most popular tier of LEED certification in Texas, representing 42.5% of all "New Construction" and "Core and Shell" projects certified in the State – based on data from April 2002 until April 2020 (USGBC, 2020). The seven categories of which credit can be allocated towards certification in the LEED 2009 version are: (1) sustainable sites; (2) water efficiency; (3) energy and atmosphere; (4) materials and resources; (5) indoor environment quality; (6) innovation; and (7) regional priority credit. Despite the widespread adoption of LEED, diverse critiques to the program are available in the literature (Wu et al., 2016); among them, the point system in which the program is based on is a major one. According to different authors (Humbert et al., 2007; Kwok and Grondzik, 2018), the program's credit system may lead to a "point chasing mentality" – i.e., owners and builders may limit themselves to adding only the minimum and easiest sustainability features in the project to achieve the desired certification (Sandoval and Prakash, 2016). Another aspect in the LEED scheme, is that some categories are more representative than others in the credit system (e.g., "materials and resources" category corresponds only to 14 out of the 100 possible points, while the "energy and atmosphere" category corresponds to 35 points) (Sandoval and Prakash, 2016). Furthermore, some credits are more difficult to achieve than others – as demonstrated by Wu et al. (2016), "materials and resource" and "energy and atmosphere" related points are more difficult to obtain than "innovation" credits. As a consequence, some projects are certified without a single credit in these categories that are harder to obtain credits in (Wu et al., 2016).

Even though Case Study A and B were seeking LEED Silver certification, the use of recovered building components (e.g., doors, windows) and CW reuse on-site were not practices adopted in either case study due to an owner's request. Such guidelines are reflected in both projects' LEED scorecards, which shows zero points for all categories related to materials and building components reuse (i.e., MRc1.1, MRc1.2, and MRc3) (USGBC, 2018; 2019a). While the reasoning behind not adopting on-site CW reuse is not clear, opportunities existed and were identified in the proposed approach. Specifically, it was estimated that 17.4 m^3 (40.4 tons) and 10.5 m^3 (23.5 tons) of concrete waste could have been reused on-site for Case Study A and B, respectively. These estimates are equivalent to 5.6% and 3.0% of the total concrete waste estimated for each project.

Notably, if on-site waste storage was not an impediment and a three-month time constraint was imposed on Case Study A, a potential reuse of 9.5% of the total concrete waste is estimated (equivalent to 68.9 tons). Such significant concrete waste reuse opportunity identified for Case Study A is primarily due to the building's architecture and large quantity of concrete pours and backfilling activities executed on the underground levels. On the other hand, even if a three-month time constraint was imposed for Case Study B, the percentage of concrete waste for reuse would still have been low. Less opportunities for on-site concrete waste reuse are available for Case Study B mainly due to the building's architecture – i.e., high-rise slender building with only one underground level – which required less backfilling activities. Nonetheless, even with a low percentage of concrete reuse, environmental and economic benefits such as reduction of transportation, disposal, recycling costs, and clean dirt over-ordering, could have been achieved (WRAP, 2008; Wankhade et al., 2014; Tam, 2011).

The total amount of concrete waste estimated for recycling in Case Study A is 221.1 m^3 (513.6 tons), and in Case Study B is 281.3 m^3 (653.4 tons). These estimates were validated with actual data from the waste hauling tickets; the difference between the concrete recycling estimate (513.6 tons) and actual data (607.2 tons) for Case Study A is 15.4%, and for Case Study B is 29.3% (653.4 tons estimated, and 924.4 tons actually recycled). Such variations are attributed to higher diversion rates achieved on the projects. That is, from the waste hauling tickets, Case Study A and B achieved concrete diversion rates of 93% and 86%, respectively; therefore greatly surpassing the 75% rate proposed in the CWMP of the studies, which was used to perform the estimates. Notably, the use of historical data of previous projects' diversion rates provides an opportunity to refine the estimates of recycling quantities, and consequently provide a more accurate CWMP. For instance, if α_{Concrete} used for the estimates was 80%, the variance between estimate and actual quantities would have been 9.8% and 24.6% for Case Study A and B, respectively. In regards to drywall recycling, 4,287.0 m^2 (52 tons) and 2,863.4 m^2 (34.4 tons) of the material could have been recycled for Case Study A and B, respectively, based on the national average of 28% recycling. The economic feasibility of drywall recycling is intimately related to transportation and disposal costs (i.e., landfill tipping fees) (Marvin, 2000). Texas has one of the lowest disposal costs in the country, which imposes a barrier to drywall recycling, additionally to the lack of facilities in Central Texas (Burns and McDonnell, 2017). Limiting the disposal of drywall waste into landfills is an option to foster the drywall recycling enterprise in the region; an example is Washington state, which adopted this policy, yielding positive results (Cochran et al., 2007a).

3.7 Conclusions and Future Research

This chapter proposed algorithms to estimate quantities of concrete and drywall waste generation for on-site reuse and off-site recycling using a temporal-based approach – i.e., based on sequential sections of building construction determined in the schedule – therefore allowing CW R&R planning as construction progresses. Additionally, the proposed algorithms were integrated with 4D-BIM to enhance planning and enable visualization of CW performance throughout construction – one major expectation of stakeholders' on BIM for CWM, highlighted by Akinade et al. (2018). Two different case studies from Central Texas were described and used to demonstrate the algorithms, the case studies represent typical mid and high-rise building construction, which are prevalent in large cities in Texas. Concrete waste generation and off-site recycling estimates were validated with ground truth data. Furthermore, percentage of materials wasted, and WGR of different nonresidential buildings in North America reported in the literature were used to validate concrete and drywall waste estimates. Based on the proposed approach, it was estimated that 40.4 tons and 23.5 tons of concrete waste could have been reused on-site for Case Study A and B, respectively. While the actual reuse of these quantities is dependent on the volume of clean fill required in the backfilling activities (which are usually not quantifiable through BIM), the algorithms and 4D-BIM enabled visually planning for concrete waste reuse opportunities – a practice that is often not formally planned.

Strengths of the approach presented in this chapter rely on streamlining estimates of CW for R&R with the use of data commonly available and easily retrievable in construction projects, therefore facilitating detailed CWM planning. Specifically, the application of the proposed approach is dependent on the availability of: (1) BIM with the 3D geometry of elements generating concrete and drywall waste (i.e., structural elements, and drywall partitions) with minimum LOD 300; (2) construction schedule; and (3) contractors' purchasing records of concrete and drywall materials. On the other hand, one limitation of the proposed approach is its dependency on the accuracy of purchasing records and BIM provided by the project management teams. Discrepancies between the elements build on-site and BIM may cause variations in the CW estimates, differences may also arise due to purchasing strategies adopted for each project, or significant rework activities that are not reflected in the construction schedule.

As pointed out by Akinade et al. (2018), most existing CWM tools rely on project-specific or location-specific information, which hinders the application of these CWM tools to projects of different contexts. As such, a contribution of this proposed model to the body of knowledge is an approach for estimating CW generation, on-site reuse, and off-site recycling quantities of two major waste streams, without the use of such local/regional information. A second contribution of the study presented in this chapter is expanding the body of knowledge of 4D-BIM applications to CWM. While 4D-BIM for CWM has been gaining momentum in recent years (Jupp, 2017), the applications available in the literature are limited (discussed in Section 3.2.2). As demonstrated by Charef et al. (2018), 4D-BIM is still primarily associated with safety management, planning and sequencing tasks, and project progress monitoring. As such, this chapter contributed specifically to demonstrating the use of 4D-BIM for CW R&R planning at the project-level. Often times CWM is perceived as a low priority objective on construction projects (Teo and Loosemore, 2001; Jain, 2012; Mahpour, 2018). In this context, contributions of this chapter to the body of practice include: (1) enhancing CWM planning through automated – i.e., BIM-based – and more convenient estimations of CW R&R quantities; and (2) proposing algorithms for the visual demonstration of waste performance throughout construction activities, which contributes to team communication and cooperation around the projects' CWM goals.

Notably, the algorithms presented in this chapter focus on concrete and drywall waste streams; in order to develop a more comprehensive application of 4D-BIM for CW R&R planning, algorithms for the estimation of other major waste streams (e.g., wood and masonry) should be developed considering its different particularities. Generating the CW R&R 4D simulations was not an automated process. As such, challenges existed, especially for the concrete waste stream, in which QTO manipulations were necessary to discount the volumes of steel reinforcement from the structural elements, and further calculations were necessary due to the estimate of waste for on-site reuse. Filtering specific families of 3D elements in BIM, generating the QTO's (discounting the volume of steel reinforcements according to the type of structural elements, in the case of the concrete algorithm), and integrating the BIM with the 4D-simulation software are examples of activities that could be further automated through the use of scripts. Considering this, future work should include automation efforts of the proposed algorithms with generative design tools. The use of such generative design tools would enable prompt CW R&R estimations, and convenience and practicality to the construction industry practitioners in generating the 4D simulations. Lastly, applying the presented approach to projects of different types (e.g., residential, industrial) and geographic locations enables developing better national recovery estimates for building constructions, thus aligning with the EPA's (2009b) aim.

Chapter 4: Circular Economy in the Built Environment

This study was approved by The University of Texas at Austin Institutional Review Board (IRB) – Federal Wide Assurance (FWA) number 00002030.

4.1 Introduction

Demand for materials and energy is largely driven by constructing, maintaining, and operating the built environment (Krausmann et al., 2017; WBCSD, 2018). Notably, the so-called building "lifecycle" is not yet cyclic (Crowther, 2005), and the construction industry is still predominantly based on a linear economic model of high natural resource consumption and low resource recovery, popularly known as "take-make-dispose" (Anastasiades et al., 2020; Archaya et al., 2018). The construction industry is considered the world's largest raw materials consumer (Zimmann et al., 2016; Ghaffar et al., 2020), consuming about 50% of the global steel production and more than 3 billion tons of raw materials annually (WEF, 2016). Specifically in the United States (U.S.), consumption of raw materials for construction of the built environment dramatically increased after the World War II and continues rising (Matos, 2017). Additionally, it is estimated that around three-quarters of all raw materials use in the U.S. is directed only to construction activities (Matos, 2017), with low recovery rates (EPA, 2009a). Despite efforts to maximize recycling rates, this continuous growth of materials consumption precludes closing resources loops (Krausmann et al., 2017). As a result, such linear economic model produces negative externalities to the environment – e.g., high emissions of carbon dioxide (CO_2) (IEA, 2019), pollution of water, soil, and air (WEF, 2016), and high construction and demolition (C&D) waste generation (Cheshire, 2016). Furthermore, this linear economic model promotes an unsustainable development, and poses risks to businesses, such as raw materials supply disruptions and price fluctuations (WEF, 2020; Zimmann et al., 2016; UNEP, 2016). Notably, decoupling resource consumption from economic growth is imperative for a sustainable development (UNEP, 2011; UNEP 2016; IRP, 2017), and different Sustainable Development Goals (SDG) were outlined by the United Nations (UN) (2015) focusing on addressing unsustainable resource consumption and built environment issues – specifically goals 9, 11, and 12.

On the opposite end of the spectrum of this inefficient and unsustainable linear economic model, is the Circular Economy (CE) – which has gained increasing attention during the last decade (Anastasiades et al., 2020; Hossain et al, 2020; Ranta et al., 2018). Despite differences in its schools of thought (EMF, 2016a; Zimmann et al., 2016) and definitions (Kirchherr et al., 2017), the CE model has the ultimate goal of retaining resources circulating at their highest value within planetary boundaries, in a manner that no additional natural resources are needed to produce materials, and the discarded materials are not viewed as waste (Cheshire, 2016; Desing et al., 2020; Potting et al., 2017). Besides circularity of resources in closed loop systems, the CE model also focuses on a better management of the resources by refusing, rethinking and reducing unnecessary consumption – examples of strategies include dematerialization of products, intensification of products use, and increase of manufacturing efficiency (Potting et al., 2017). In summary, foundations of the CE model rely on a better management of resources by reducing consumption, and replacing the 'end-of-life' concept with reusing, recycling, and recovering materials and components (Kirchherr et al., 2017; Pomponi and Moncaster, 2017). When it comes to the built environment, it is necessary to achieve settlement patterns that require low resource input and that facilitate the circulation of materials and resources. Nevertheless, the efficiency of circulating resources and recovering materials and components at a building's end-of-life is directly influenced by decisions made early in the design of the project (Guy et al., 2006; Zimmann et al., 2016). As such, these two stages of the building lifecycle (i.e., design and end-of-life) are critical and closely interconnected in the CE model.

Studies demonstrate that part of the existing building stock in the U.S. is disposed of before their intended life span, and this is not necessarily due to the deterioration of its physical conditions (Cheshire, 2016; O'Connor, 2004; Webster, 2007). Unfortunately, great part of the existing building stock was not designed for disassembly and resource recovery (Archaya et al., 2018; Pantini and Rigamonti, 2020; Stephan and Athanassiadis, 2018); in fact, very few buildings have been designed taking into account their entire lifecycle and end-of-life treatment (Rios et al., 2015). As such, a great part of construction materials end up as waste during the building's end-of-life, which increases environmental costs and creates a risk of resource scarcity (Akanbi et al., 2018; Debacker and Manshoven, 2016; Mangialardi and Micelli, 2018). Circular strategies aim to prolong the life of components and products (in the context of this study, buildings), and close material flows once the end-of-life of this product is inevitably reached (Bocken et al., 2016; Nussholz and Milios, 2017). Several circular strategies are discussed in the literature; however, the application of these strategies *in practice* is dependent on external factors, as well as synergies and collaboration between distinct stakeholders along the value chain (Geldermans, 2016; Wells and Seitz, 2005). For instance, when it comes to a building's end-of-life C&D waste management, factors such as landfill tipping fees, state of local recycling industry, deconstruction labor speed and costs, presence of market for salvaged materials, logistics, and materials recuperation costs can largely influence – or hinder – the adoption of circular strategies by construction companies (Kibert et al., 2001; Guerra et al., 2020). Such collaboration between different stakeholders along the construction value chain is essential to develop a fully circular built environment (Zimmann et al., 2016). Notably, developing a fully circular built environment – i.e., buildings that are designed, operated, maintained, and deconstructed according to CE principles (Pomponi and Moncaster, 2017) – is challenging, and still not widely adopted (Zimmann et al., 2016).

Nevertheless, an increasing number of countries started to take advantage of the financial and environmental opportunities of transitioning towards a circular built environment (WBCSD, 2018). Organizations such as the World Economic Forum (WEF) estimate that adoption of CE principles in the construction sector could result in over U.S. $100 Billion per year due to improved productivity (WEF, 2016). Moreover, the European Union (EU) estimates that improvement in construction resource productivity could save up to € 23 Billion per year for European businesses and create up to 150,000 jobs (EC, 2016). Based on these substantial opportunities, an increasing number of policies and roadmaps are being implemented, especially in Europe and Asia, enhancing resource efficiency in the built environment, and pushing forward the adoption of practices aligned to the CE model (Jones and Comfort, 2018; McDowall et al., 2017). Notably, the U.S. construction industry is one of the largest in the world, and is a key sector for the American economy (Barbosa et al., 2017). Transitioning from a linear into a circular built environment has a substantial potential for economic growth and to futureproof the construction sector, which would be less dependent on raw materials (WBCSD, 2018). As such, investigating the *state of practice* of circular strategies adoption is necessary in order to pinpoint current barriers, and enablers for a transition towards a CE model in the built environment in the U.S.

A review of the existing body of knowledge reveals that the majority of publications related to CE in the built environment are from European and Asian countries (Benachio et al., 2020; Hossain et al., 2020), and to the best of the authors' knowledge, no studies are concerned to the state of practice of circular construction in the built environment in the U.S. In this context, the overarching objective of the study presented in this chapter is to assess U.S. architecture, engineering, and construction (AEC) industry stakeholders' awareness of CE in the construction industry, as well as, to better understand the major challenges and enablers of adopting circular strategies in construction projects. Specifically, this study aims to: (1) *quantitatively* assess AEC stakeholders awareness and adoption of major circular strategies in construction projects; (2) understand the factors that prevent stakeholders from adopting these circular strategies *in practice*; and (3) examine stakeholders' perceptions on enabling factors for a transition towards a CE model in the built environment in the U.S. A mixed-methods approach was utilized to achieve these objectives. Questionnaires were delivered to *quantitatively* assess the participants' awareness and adoption of major circular strategies that were identified through a literature review. Semi-structured interviews were conducted with AEC professionals of different backgrounds to *qualitatively* assess their perceptions in three domains of knowledge (i.e., current construction practices, circular strategies implementation barriers, and circular economy enablers). Notably, the study presented in this chapter provides an assessment of U.S. AEC stakeholders views of circularity; yet, aspects such as the current U.S. political scenario and budget shortages are not covered. The culmination of this study fills an existing gap in the literature, and enables a better understanding of the state of practice of circular construction in the U.S. Furthermore, it contributes to a much needed debate around the existing bottlenecks in the industry, and serves as a stepping-stone for future CE studies in the U.S., thus expanding the limited body of knowledge.

4.2 Background Research

There is a consensus in the literature that adopting strategies to reduce waste generation, extend building use, and facilitate resource recovery are enablers to transition towards a CE in the built environment (Hossain et al., 2020). Nevertheless, differences in definitions and terminologies in the sustainability and CE domains of knowledge are common (Bocken, 2016; Cossu and Williams, 2015). For instance, some authors name the aforementioned strategies as "CE principles" (Cheshire, 2016), while others refer to them as "CE aspects" (Adams et al., 2017), "CE strategies" (Foster, 2020), or "CE practices" (Benachio et al., 2020). This study adopts the terminology "circular strategies" by Nussholz and Milios (2017), Bocken et al. (2016), and Rasmussen et al. (2019). Section 4.2.1 is devoted to identifying major circular strategies that are suggested in the literature as means of achieving a CE in the built environment, and providing these strategies a common definition. Notably, this study focuses specifically on strategies applied during the design and end-of-life phases of construction projects; this is due to the significant impact that these phases have in a project in terms of the ability to recover resources (Akanbi et al., 2018; IRP, 2020), and C&D waste generation (Kibert, 2008). Section 4.2.2 synthesizes studies related to stakeholders' awareness of CE for the built environment, and studies related to the state of practice of circular strategies adoption.

4.2.1 Design and End-of-Life Circular Strategies

C&D waste generation is an evident and serious issue in the built environment. As such, large attention in the literature is directed to strategies for waste reduction. Examples include C&D waste reduction through government legislation, use of low waste technologies (e.g., pre-fabrication, steel formwork), BIM-based design coordination and design out waste techniques, and financial-based incentives (Lu and Yuan, 2011; Mahpour and Mortaheb, 2018; Liu et al., 2020). Besides reduction of waste generation, resource efficiency and circularity are other key principles of the CE model (Acharya et al., 2018). Circular strategies aim to extend the useful life of materials and components (i.e., slow resource loops) through repair, refurbishment, or remanufacturing, and subsequently close these resource loops through recycling once the end-of-life is inevitably reached (Bocken, 2016). Table 4-1 summarizes strategies proposed by different authors as means of achieving building circularity. Notably, design for disassembly and design for adaptability and flexibility are popular strategies cited by almost every author in Table 4-1. The circular strategies “facilitate access to building services” and “build in layers”, pointed out by Zimmann et al. (2016) and Cheshire (2016) respectively, are interconnected to the concept of “shearing layers”. This concept was first introduced by the architect Frank Duffy (Brand, 1994), who proposed separating buildings into four layers with different lifespans – i.e., shell, services, scenery and set. This clear delineation between building components of different lifespans facilitates refits and refurbishments in the building, thus promoting adaptability throughout its life (Cheshire, 2016). Moreover, it reduces C&D waste generation during the operation of the building by making short-lived components easily accessible (Cheshire, 2016).

Another popular group of circular strategies revolve around modularization, prefabrication, and standardization of building materials and components. While these strategies have different definitions (provided in Table 4-2), often times their adoption is interconnected (e.g., modularized bathrooms are prefabricated) and they are discussed together in the literature. For Zimmann et al. (2016) and Minunno et al. (2018), modularization and prefabrication are key for developing a circular built environment. This is mainly due to on-site material waste reduction, and facility to reuse and repurpose components. Moreover, standardization of materials and components enables their reuse in multiple buildings without the need for significant adjustments, thus making this strategy also crucial for a circular built environment (Geldermans, 2016).

Materials selection and specification for building construction is another topic widely discussed in the circular construction literature. For Geldermans (2016) and Hoissain et al. (2020) materials should be durable and of high quality (i.e., with functional performance), with sustainable origin (i.e., renewable), non-toxic, and consistent with biological or technical cycles. For Minunno et al. (2018) and Adams et al. (2017), reclaimed and recycled materials should be prioritized and specified during the design stage. Minunno et al. (2018) also suggests incorporating C&D waste and by-products into new building components as a circular strategy. Regarding the end-of-life of construction projects, selective demolition, deconstruction (or disassembly), closed-loop and open-loop recycling are cited as strategies to leverage circularity in the built environment.

Reference	Circular Strategies Suggested
Adams et al. (2017)	• Design for disassembly • Design for adaptability and flexibility • Design for standardization • Design out waste • Design for modularity • Specify reclaimed and recycled materials • Deconstruction • Selective demolition • Reuse of products • Closed-loop recycling • Open-loop recycling

Table 4-1: Circular strategies literature review

Cheshire (2016)	• Build in layers • Design out waste • Design for adaptability • Design for disassembly • Materials selection
Geldermans (2016)	• Design for adaptability • Materials selection • Standardization of materials and components
Hossain et al. (2020)	• Materials selection • Design for disassembly • Modular and prefabricated components • Recovery schemes • Data sharing • Guidelines and training for demolition companies
Minunno et al. (2018)	• Waste reduction • C&D waste as by-product • Reuse of products • Design for adaptability • Design for disassembly • Materials selection • Tracking systems and components
Zimmann et al. (2016)	• Design for adaptability • Modularization • Prefabrication • Facilitate access to building services

Table 4-1, continued: Circular strategies literature review

Based on the aforementioned review, a list of twelve major design and end-of-life circular strategies is summarized in Table 4-2. Notably, differences in the granularity and aggregation of these strategies was observed depending on the authors. For instance, for the Waste and Resources Action Programme (WRAP, 2009), the "design out waste" circular strategy encompasses five principles: (1) design for reuse and recovery; (2)

design for off-site construction; (3) design for materials optimization; (4) design for waste efficient procurement; and (5) design for deconstruction and flexibility. Meanwhile, for other authors (Adams et al., 2017; Cheshire, 2016; Graham, 2005; Kissel et al. 2012; Nussholz and Milios, 2017; Webster, 2007), “design for adaptability and flexibility” and “design for disassembly” are independent circular strategies. Moreover, different terminologies were noted with regards to “selective demolition”, “deconstruction”, and “disassembly”; this study, however, adopts the definitions proposed by Hurley et al. (2001), which are reflected in the descriptions of these corresponding strategies, shown in Table 4-2. Lastly, relevant studies related to sustainability and CE that suggest the use of these strategies as means to achieve circular building construction are also listed in Table 4-2.

Strategy	Circular Strategy	Phase	Description	Reference
C.S. #1	Selective demolition	EoL	This strategy is composed of two parts: the first part, named “soft stripping”, seeks the identification and removal of hazardous wastes of the building (e.g. asbestos), followed with the removal of components and materials that can be reused or sold for reprocessing (e.g. metals). The second part relies on conventional demolition procedures of the remaining building.	• Cha et al. (2012) • Coelho and de Brito (2011) • Pantini and Rigamonti (2020)

Table 4-2: Major design and end-of-life circular strategies

C.S. #2	Deconstruction (or disassembly)	EoL	Deconstruction is the process of disassembling buildings with the intention of components and materials' reuse, avoiding demolition through the recovery of reusable materials.	• Huukah et al. (2015) • Jimenez-Rivero and Garcia-Navarro (2017) • Kibert et al. (2001) • Sanchez et al. (2019)
C.S. #3	Specify recyclable and reusable materials	D	Use of recycled and reused (i.e. salvaged) materials during design specification. Additionally, proposing the use of materials that can be recycled at the end-of-life of the project (e.g. light weight steel).	• Akadiri et al. (2012) • Arora et al. (2020) • Guy and Ciarimboli (2008) • Miflin et al. (2017) • Rasmussen et al. (2019)
C.S. #4	Design out waste	D	Design using a set of strategies with the purpose of minimizing waste generation. For instance, design for off-site construction, and design for materials optimization.	• Akadiri et al. (2012) • Miflin et al. (2017) • Osmani et al. (2008) • WRAP (2009)

Table 4-2, continued: Major design and end-of-life circular strategies

C.S. #5	Design for modularity (or modularization)	D	Use components and materials that are compatible with other systems both dimensionally and functionally.	• Akadiri et al. (2012) • Kamali and Hewage (2016) • Kyro et al. (2019) • Ortlepp et al. (2017) • Osmani et al. (2008)
C.S. #6	Closed-loop recycling (or up-cycling)	EoL	This recycling system seeks to remanufacture material mass into the same product (e.g. concrete waste into regenerated concrete; steel recycling into new reinforcement steel bars).	• Vefago and Avellaneda (2013) • Yuan et al. (2011)
C.S. #7	Open-loop recycling (or down-cycling)	EoL	In this recycling system, material mass are remanufactured into different products (e.g. crushed concrete waste into roadbeds) – usually of lower value.	• Vefago and Avellaneda (2013) • Yuan et al. (2011)
C.S.#8	Design for adaptability and flexibility	D	Design with the purpose of modifying/adapting a building during the course of its life. For instance, over dimensioning structure to enable modification of building use.	• Debacker et al. (2017) • Kissel et al. (2012) • Sadafi et al. (2014) • Webster (2013)

Table 4-2, continued: Major design and end-of-life circular strategies

C.S. #9	Design for standardization (or standardization)	D	Standardization of building materials, components, and connectors with the purpose of simplifying the disassembly and sorting processes at the end-of-life.	• Guy and Ciarimboli (2008) • Ortlepp et al. (2017) • Osmani et al. (2008) • Rios et al. (2015)
C.S. #10	Designing in layers	D	Designing building in layers to facilitate separation of components with different life spans. For instance, separation of superstructure and facades to facilitate renovations; separation of internal walls and structure to facilitate renovations.	• Mangialardi and Micelli (2018) • Miflin et al. (2017) • Ortlepp et al. (2017) • Pushkar and Shaviv (2016)
C.S. #11	Design for disassembly	D	Design with the purpose of facilitating building recovery and reuse of its components and materials at the end of life.	• Akanbi et al. (2019) • Akinade et al. (2015b) • Guy and Ciarimboli (2008) • Miflin et al. (2017) • Rasmussen et al. (2019) • Vanegas et al. (2018)

Table 4-2, continued: Major design and end-of-life circular strategies

C.S. #12	Design for prefabrication (or prefabrication)	D	Prefabrication is the manufacturing process that happens outside the construction jobsite (i.e. on a specialized facility), in which materials are combined to form a component, and this component will be used for final installation in the project. Prefabrication can be performed at different levels (e.g. from component manufacture and pre-assembly off-site, to whole-building prefabrication off-site).	• Jaillon and Poon (2008) • Jiang et al. (2019) • Yuan et al. (2018)

Note: Phase = D (Design); EoL (End-of-life);

Table 4-2, continued: Major design and end-of-life circular strategies

4.2.2 Circular Construction Awareness and State of Practice

Literature focusing in CE for the construction sector is still in its infancy (Pomponi and Moncaster, 2017) – especially in North America (Benachio et al., 2020; Ghisellini et al., 2018; Hossain et al., 2020). One of the most popular group of studies in the CE literature focuses on construction stakeholders' awareness and knowledge of the concept, as well as, barriers and opportunities for the transition towards a CE model in the built environment (Benachio et al., 2020; Hossain et al., 2020). Table 4-3 synthesizes relevant studies related to the aforementioned domains of knowledge. As demonstrated in

Table 4-3, to the best of the authors' knowledge, no study has yet been published with such focus for the U.S. AEC industry context, thus, revealing a gap in the literature.

Reference	Objective	Methodology	Location
Adams et al. (2017)	Collect an industrywide perspective of CE awareness, challengers, and enablers.	Surveys and Workshops	United Kingdom
Anastasiades et al. (2020)	Define CE and sustainability. Explore to which extent circular strategies are being adopted in bridge construction.	Literature Review	Belgium
Chang and Hsieh (2019)	Explore the state of practice (i.e. challenges and enablers), stakeholders awareness, and future potentials of CE in the built environment.	Interview and Case Study	Taiwan
Ghaffar et al. (2020)	Investigate current practices of C&D waste management and circular construction awareness.	Interviews and Surveys	United Kingdom
Hart et al. (2019)	Identify the barriers and enablers for the CE in the built environment.	Literature Review	United Kingdom
Huang et al. (2018)	Provide an overview of C&D waste management policies. Identify barriers in treating C&D waste according to a CE model.	Literature Review and Interviews	China
Mahpour (2018)	Identify and prioritize potential barriers of embedding circular strategies in C&D waste management.	Literature Review and Surveys	Iran

Table 4-3: Studies related to circular economy awareness and state of practice

Mangialardi and Micelli (2018)	Demonstrate the application of circular strategies in three buildings' case studies.	Case Studies	United Kingdom Netherlands France
Nussholz and Milios (2017)	Provide an overview of business models innovations of six different companies that facilitate the adoption of circular strategies.	Case Studies	Europe *(Specific countries were not disclosed)*
Van Bueren et al. (2019)	Explore successful paths and barriers to introduce circular building construction to the Taiwan region.	Case Studies and Interviews	Taiwan

Table 4-3, continued: Studies related to circular economy awareness and state of practice

4.3 RESEARCH METHODOLOGY

The study presented in this chapter used a mixed-methods approach of online survey and semi-structured interviews, as illustrated in Figure 4-1. Quantitative (i.e., survey) and qualitative (i.e., interviews) data collection are viewed as complimentary to each other (Jick 1983, p. 135; Toepoel 2016, p. 2), and are gaining popularity on phenomenological studies (Mayoh and Onwuegbuzie, 2015). A phenomenological study focuses on collecting people's experience on a specific phenomenon in a manner to be used as qualitative evidence of that phenomenon (Creswell 2012, p.76; Mayoh and Onwuegbuzie, 2015). In this study's context, the phenomenon studied is the awareness and adoption of circular strategies, and barriers for a transition towards circularity in the built environment in the U.S. Specifically, the survey's *quantitative data* was used to assess stakeholders' awareness and adoption of circular strategies, and the interview's *qualitative data* was used to assess current construction practices, barriers in the adoption of circular strategies, and CE enablers.

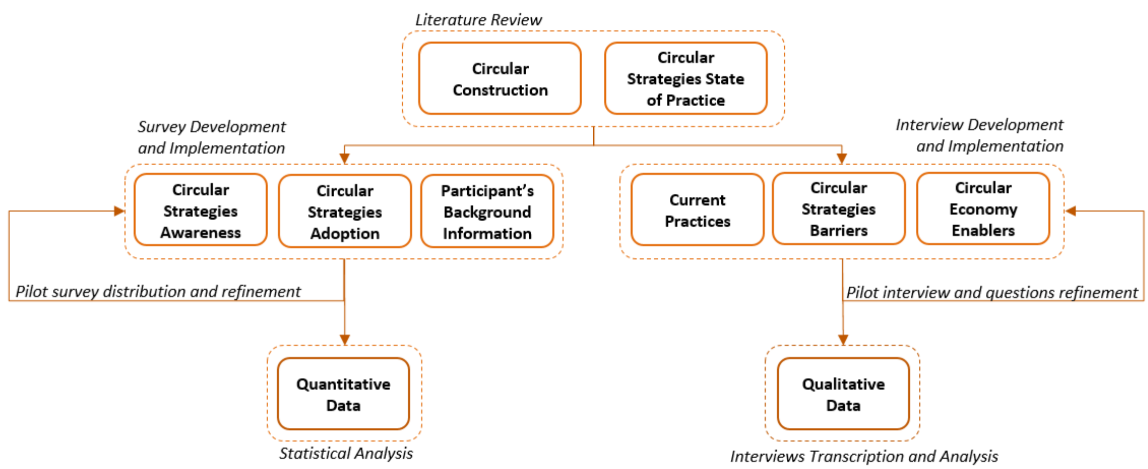


Figure 4-1: Research methodology

4.3.1 Quantitative Data Collection

The twelve major circular strategies summarized in Table 4-2 were used as a stepping-stone for the development of the online survey, which had seventeen questions divided into three sections: (1) participant's background information; (2) circular strategies awareness; and (3) circular strategies adoption – refer to Appendix F to see the survey questions in detail. Notably, the survey participants had access to the definitions of each circular strategy, as provided in Table 4-2. Five-point Likert scale questions were used to quantitatively assess the level of awareness and adoption of the circular strategies – i.e., rating was from '1' as the lowest to '5' as the highest. One question asked participants to rank the strategies from most important to least important in order to achieve a circular built environment, one question focused on the implementation of the circular strategies, and the remaining questions focused on the participant's background and demographics. Mechanisms such as an initial excluding question to eliminate participants out of the study's scope of work, and minimum completion time are suggested in the questionnaire survey literature (Brace 2018, p. 45; Malhotra, 2008); as such, they were adopted to assure the quality of the responses. Furthermore, a pilot survey was deployed prior to the launch of the actual survey in order to verify the clarity of the instructions and to perform necessary adjustments. Three individuals tested and reviewed the pilot survey. Finally, the actual data collection was performed during three months and yielded 130 valid responses.

4.3.2 Qualitative Data Collection

A document with 14 open-ended questions related to three domains of knowledge (i.e., current construction practices, circular strategies implementation barriers, and circular economy enablers) was developed and used as a guide during the semi-structured interviews – for the full list of questions see Appendix E. Notably, every question in the list was asked to each participant, although not always following the exact order demonstrated in the semi-structured document. Furthermore, follow-up questions were asked when necessary. The recruiting of participants was performed through a snowball sampling method (Noy, 2008; Patton 2002, p. 243). Targeted participants were those in the AEC industry in the U.S. A sample of participants from different types of companies (i.e., general contracting companies, architectural and design companies, owners, and consulting and research companies), with different roles (e.g., project engineer, designer, director of sustainability), and with varying industry experience was composed for this study. In sum, the three aforementioned criteria were used to form a purposeful sample of participants – i.e., a sample able to meet the objectives outlined for the study (Patton 2002, p. 243). Table 4-4 provides background information of the interviewees – the average industry experience of the participants was 16 years, and the average length of the interviews was 50 minutes. Figure 4-2 is a summary of the interviewees by State. All semi-structured interviews were conducted online and were recorded. The interviews' recordings were transcribed into text with the aid of an Artificial Intelligence (AI) online software. The interviews' transcripts were individually reviewed and analyzed by the authors afterwards. The qualitative data collection was discontinued based on the saturation criteria (Corbin and Strauss 2015, p. 135; Saunders et al., 2017), in which there is a diminishing return of new information with further data collection (Mason, 2010). Furthermore, the sample size of seventeen participants was deemed suitable for phenomenological studies – Creswell (2012, p. 81) recommends 5 to 25 praticipants, Morse (1994, p. 225) suggests at least 6 participants, Bertaux (1981, p.35) recommends a minimum of 15 participants for any type of qualitative research (e.g., phenomenological, grounded theory, ethnographic), and Kuzel (1992) recommends 12 to 20 participants when there is heterogeneity in the participants' background.

Interviewee	Location	Company Size - by Employee	Current Role	Years of Exp.	Type of Company
A	Texas	5,001-10,000	Project Engineer	2	GC
B	Texas	5,001-10,000	Software Development and Tech. Implementation	9	GC
C	New Jersey	1,001-5,000	Senior Project Manager	20	GC
D	Colorado	5,001-10,000	Project Manager and Sustainability Leader	8	GC
E	Colorado	1,001-5,000	Operational Excellence: Process Improvement	32	DS + GC
F	Texas	501-1,000	Project Manager	5	GC
G	California	10,001+	Project Manager and Advisory services	8	Consulting/ Research
H	New York	1-200	Architect	16	DS
I	New York	10,001+	Senior Engineer in the Technology and Research Group	5	Consulting/ Research

Table 4-4: Interviewees' background information

J	New Mexico	10,001+	Construction Manager	28	Owner
K	California	1,001-5,000	Vice President of Quality and Sustainability	35	GC
L	Colorado	1,001-5,000	Director of Sustainability	20	GC
M	Virginia	5,001-10,000	Project Engineer	2	GC
N	Washington	5,001-10,000	Construction Manager	33	Owner
O	Texas	1,001-5,000	Project Manager	30	GC
P	Texas	501-1,000	Virtual Design and Construction (VDC) Manager	11	GC
Q	Texas	5,001-10,000	Project and Sustainability Manager	8.5	DS + GC

Table 4-4, continued: Interviewees' background information

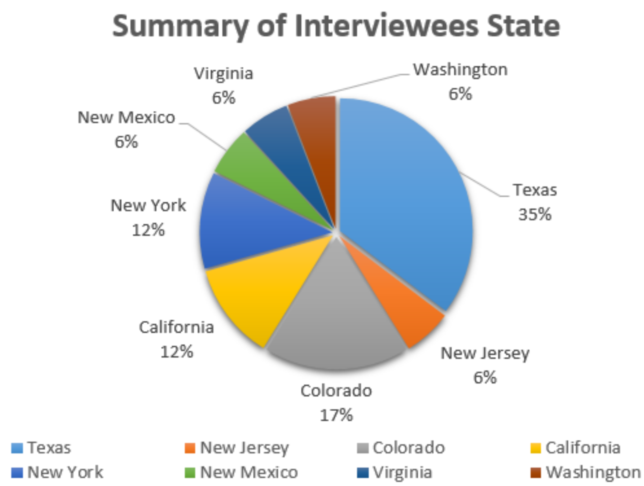


Figure 4-2: Summary of Interviewees by State

4.4 RESULTS

4.4.1 Survey Results

Figure 4-3 summarizes the profile of the 130 survey respondents according to their age, role inside the company, level of education, and Leadership in Energy and Environmental Design (LEED) accreditation. LEED is currently the most disseminated green rating system in the world and is a reference in the development of sustainable buildings (USGBC, 2021; Pulselli et al., 2007; Wu et al., 2016). Notably, the latest version of the rating system (i.e., LEED v4.1) incorporates concepts that support the advance of a CE. Examples include credits for whole-building lifecycle assessment, selection of products that are third-party verified to meet CE principles, and incentives for C&D waste reduction at source (e.g., building reuse, renovation of abandoned building, and reuse of salvage building materials) (USGBC, 2019b). The survey participants had an average age of 38 years, an average industry experience of 16 years, and comprised mainly six groups: (1) project managers; (2) owners; (3) field/site engineers; (4) designers/architects; (5) site superintendents; and (6) "others". Notably, the "others" group included participants with roles such as directors of sustainability, pre-construction engineers, quality control engineers, field workers, and project schedulers. Figure 4-4 summarizes information about the companies of the participants – i.e., the most common type of construction project and delivery method.

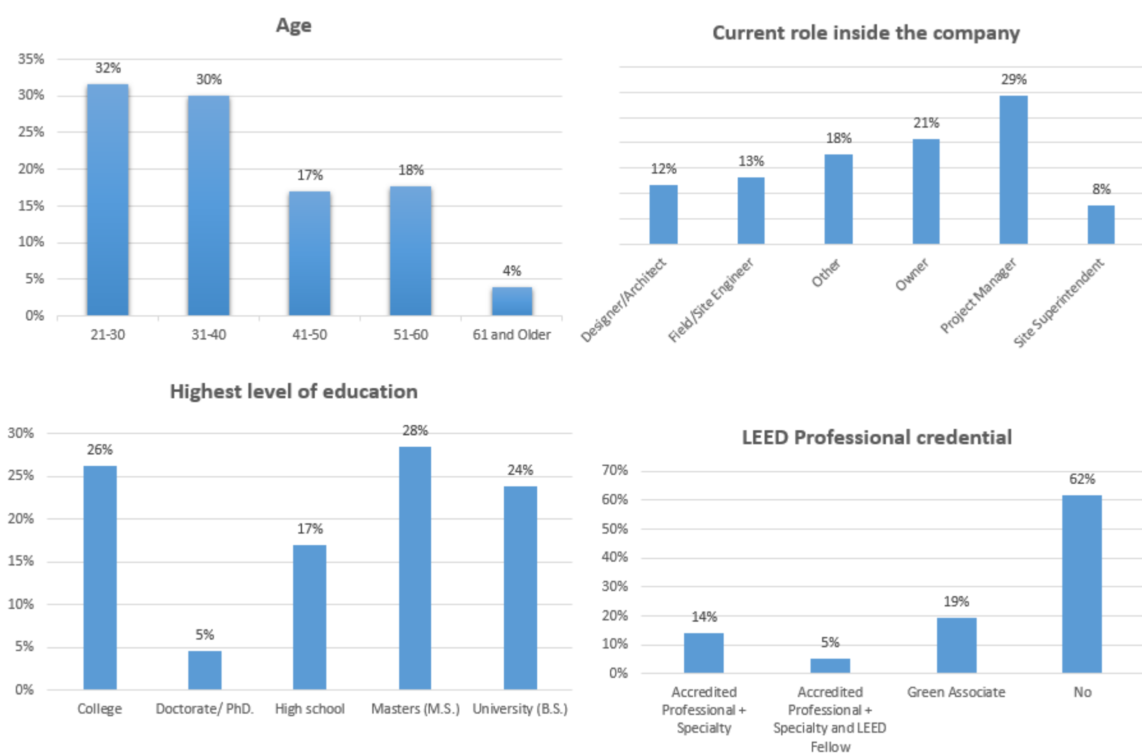


Figure 4-3: Survey Participant's Demographics

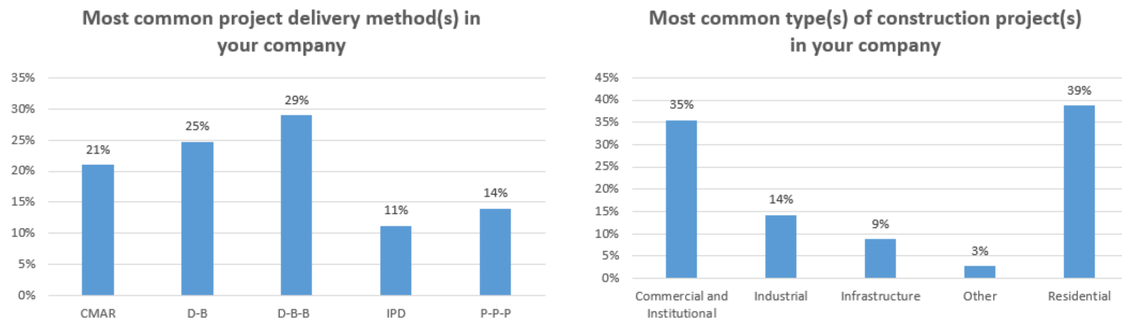


Figure 4-4: Summary of Participant's company

Analysis of variance (ANOVA) was used to determine whether there was a statistically significant difference between the level of awareness of the circular strategies according to different characteristics of the survey participants. Notably, in this study, a P value of 0.05 was used to determine whether there was a statistically significant difference between the level of awareness of the circular strategies or not (i.e., $p < 0.05$ means there was a statistically significant difference among the groups under study). Three characteristics of the participants were analyzed: (1) role; (2) education; and (3) age. The first characteristic considered was the participants' role inside their companies (i.e., designers/architects, field/site engineers, owners, project managers, site superintendents, and others). Results revealed that there was a statistically significant (i.e., $p < 0.05$) difference in the level of awareness of seven major circular strategies among the different groups of participants. Figure 4-5 summarizes the average awareness of these seven circular strategies according to each group of participants. Notably, project managers and owners were the groups with highest awareness of these strategies (i.e., green and greenish cells), and designers/architects and "others", were the groups with lowest awareness of these strategies (i.e., red and reddish cells). It is worthwhile to mention that for this survey it was used a 5-point Likert scale in which one is the lowest awareness and five is the highest awareness.

	Group 1 - Designers/Architects	Group 2 - Field/Site Engineers	Group 3 - Others	Group 4 - Owners	Group 5 - Project Managers	Group 6 - Site Superintendents
C.S. #1 – Selective Demolition	2.79	3.18	2.59	3.40	3.73	3.60
C.S. #2- Deconstruction (or Disassembly)	2.86	3.29	3.23	3.76	4.00	3.40
C.S. #5 - Modularization	2.93	3.71	2.32	3.12	3.73	3.10
C.S. #6 – Closed-loop Recycling	2.71	2.94	2.50	2.64	3.49	2.40
C.S. #9 - Standardization	3.07	3.76	2.73	3.52	3.97	3.80
C.S. #10 – Design in Layers	2.57	2.59	2.23	3.24	3.73	2.20
C.S. #11 – Design for Disassembly	2.86	2.53	2.14	3.28	3.43	2.60

** Five-point Likert scale where 1 = lowest awareness (i.e. red and reddish cells) and 5 = highest awareness (i.e. green and greenish cells)*

Figure 4-5: Average awareness of circular strategies with $p < 0.05$ according to groups of participants with different roles

The second characteristic considered was education. In this realm, one analysis compared participants who received a formal education in CE (i.e., 26% of the participants), from those who did not (i.e., 74% of the participants). This analysis was conducted to confirm whether formal education in CE in fact contributed to a higher awareness of circular strategies. As expected, there was a statistically significant (i.e., $p < 0.05$) difference in the level of awareness of almost all circular strategies between these two groups of participants (Figure 4-6) – except for circular strategy two (i.e., deconstruction) and circular strategy 12 (i.e., prefabrication), which did not present a statistically significant difference between the two groups. From this analysis it could be confirmed the important role that formal education in CE can play in a transition towards circularity in the built environment. Moreover, the level of education of the participants (i.e., high school, college, university, masters, or doctorate) was considered when analyzing their level of awareness of the circular strategies. As shown in Figure 4-7, overall, the level of awareness of the circular strategies was directly correlated to the level of education of the participants. Circular strategy two (i.e., deconstruction) was the only one in which level of awareness was independent of the level of education (i.e., there was not a statistically significant difference in awareness among the five groups).

	Group 1 - CE Formal Education	Group 2 - No CE Education
C.S. #1 – Selective Demolition	3.82	2.96
C.S. #3 – Deconstruction (or Disassembly)	4.06	3.50
C.S. #4 – Design out Waste	3.94	2.64
C.S. #5 - Modularization	4.09	2.85
C.S. #6 – Closed-loop Recycling	3.94	2.48
C.S. #7 – Open-loop Recycling	4.03	2.43
C.S. #8 – Design for adaptability and flexibility	3.91	2.96
C.S. #9 - Standardization	4.18	3.22
C.S. #10 – Design in Layers	4.00	2.61
C.S. #11 – Design for Disassembly	3.76	2.53

** Five-point Likert scale where 1 = lowest awareness (i.e. red and reddish cells) and 5 = highest awareness (i.e. green and greenish cells)*

Figure 4-6: Average awareness of circular strategies with $p < 0.05$ according to groups of participants with and without CE formal education

	Group 1 - High School	Group 2 - College	Group 3 - University (B.S.)	Group 4 - Masters (M.S.)	Group 5 - Doctorate (Ph.D.)
C.S. #1 – Selective Demolition	2.45	3.21	3.19	3.51	3.67
C.S. #3 – Deconstruction (or Disassembly)	2.95	3.53	3.71	3.92	4.83
C.S. #4 – Design out Waste	1.82	3.00	3.13	3.41	3.67
C.S. #5 - Modularization	1.95	2.94	3.29	3.89	4.00
C.S. #6 – Closed-loop Recycling	1.86	2.71	2.94	3.30	4.33
C.S. #7 – Open-loop Recycling	1.73	2.88	3.03	3.11	4.17
C.S. #8 – Design for adaptability and flexibility	2.18	3.06	3.39	3.73	3.67
C.S. #9 - Standardization	2.41	3.38	3.55	4.03	4.00
C.S. #10 – Design in Layers	2.18	2.88	3.19	3.24	3.67
C.S. #11 – Design for Disassembly	2.32	2.62	2.81	3.38	3.17
C.S. #12 – Prefabrication	3.05	3.47	4.19	4.32	3.67

** Five-point Likert scale where 1 = lowest awareness (i.e. red and reddish cells) and 5 = highest awareness (i.e. green and greenish cells)*

Figure 4-7: Average awareness of circular strategies with $p < 0.05$ according to groups of participants with different levels of education

Lastly, the participants age was used to evaluate the difference in awareness of the circular strategies. Notably, for this analysis, participants with LEED accreditation (i.e., 38%) were separated from those without (i.e., 62%), and the analysis was performed using only the participants without any LEED accreditation. The reasoning behind using this subset of participants was to evaluate whether age made any difference when participants did not receive a sustainable certification training throughout its career. The participants were divided into five different age groups (as shown in Figure 4-3); and only circular strategy eight (i.e., design for adaptability and flexibility), ten (i.e., design in layers), and 11 (i.e., design for disassembly) presented a statistically significant (i.e., $p < 0.05$) difference in awareness between the groups. Specifically, participants with age between 21 and 30 presented a significantly higher awareness of circular strategies eight, ten, and 11. It is important to note that the aforementioned circular strategies are relatively newer than other more traditional circular strategies such as prefabrication, selective demolition, and recycling. As such, one point of consideration is that, younger professionals may have started to be more exposed to these newer circular strategies, whereas older participants probably were not exposed during their formal education. Nevertheless, age did not seem to be a decisive factor for the awareness of the remaining nine circular strategies.

With regard to circular strategies adoption, 38% of the respondents mentioned that their companies were trying to implement at least one of the 12 circular strategies across every project of the company; 33% of the respondents answered that the implementation of circular strategies was a project-specific decision; 12% mentioned that their companies had no plans to implement circular strategies; and 17% were not aware of their companies plans on implementation of circular strategies. Figure 4-8 presents the circular strategies with highest and lowest average of adoption among designer/architect participants, and participants with a construction background (i.e., site/field engineers, project managers, and site superintendents). Among the designers/architects group, circular strategy three (i.e., specify reusable and recyclable materials), and 12 (i.e., design for prefabrication/prefabrication) were the ones with a highest average of adoption. Meanwhile, circular strategy ten (i.e., design in layers), and 11 (i.e., design for disassembly) were the ones with lowest average of adoption. Among participants with a construction background, circular strategy one (i.e., selective demolition) was the one with highest average of adoption, and circular strategy six (i.e., closed-loop recycling) was the strategy with lowest average of adoption.

Circular Strategies' Adoption

Group	Highest Adoption	Lowest Adoption
Designers/Architects	C.S. #3 – Specify Reusable and Recyclable Materials C.S. #12 – Design for Prefabrication	C.S. #10 – Designing in Layers C.S. #11 – Design for Disassembly
Construction Background*	C.S. #1 – Selective Demolition	C.S. #6 – Closed Loop Recycling

** i.e., site/field engineers, project managers, site superintendents*

Figure 4-8: Circular strategies adoption according to groups of participants

4.4.2 Semi-structured Interview Results

The following subsections report major findings of the semi-structured interviews according to the three domains of knowledge explored in this chapter. Appendix G presents the qualitative data analysis performed – i.e., coding dictionary and tables with responses' frequency.

4.4.2.1 Current Construction Practices

Right after introductions, each interviewee was asked to describe the relationship between design and C&D waste generation. Almost all participants indicated that the design phase of the project has a large influence in C&D waste generation; however, different perspectives were given on the same subject. Interviewee D commented on the importance of adaptive reuse of building spaces, demountable walls, and core and shell type of projects to reduce C&D waste generation throughout the building lifecycle. Interviewee F pointed out excessive rework during construction, which she attributed to overlooked items and lack of integration between design and construction stakeholders in early phases of the project. Interviewees E, O, and Q focused their answers on the selection of recyclable materials and optimization of spaces dimensions to reduce waste due to cut outs. Interviewee M reflected that C&D waste generation is a shared responsibility between the design and construction stakeholders. She highlighted that a good design can prevent waste, however, construction practices such as education of workers and subcontractors are equally important.

The implementation of circular strategies is a topic with large attention in this study. As such, the interviewees were questioned as to who currently guided/determined the adoption of these strategies in their projects. The majority of the interviewees from general contracting (GC) companies mentioned that the owner and the level of sustainable certification sought in the project (e.g., LEED certification) were the main drivers for the adoption of the circular strategies or not. Some participants from GC companies also highlighted that they had certain influence in the adoption of circular strategies depending on the stage of their involvement in the project, and the contract type (i.e., in design-build projects the GC has more influence than in hard-bid projects). On the other hand, Interviewees D and E, placed the responsibility of guiding the adoption of circular strategies in the builder's hands in conjunction with the design team. According to Interviewee D this is because not every owner is experienced enough to propose the adoption of circular strategies by his or herself. Interviewee H, who is an architect/designer, mentioned that an experienced and knowledgeable designer can have a large influence in proposing the adoption of circular strategies. Nonetheless, ultimately, the client and the budget of the project are the main drivers.

A follow-up question was whether there was any circular strategy always adopted within their projects, independent of the owner's request and project type. Interviewees A and C commented that selective demolition was a very common practice within their companies, and that in almost every brownfield project they stripped out materials with certain financial value (e.g., furniture, light fixtures, wires and conduits) in order to make savings. Interviewees E and G commented that design out waste and materials optimization were common concerns in their projects. Interviewee E gave a real-life example of customizing drywall sheets dimensions with manufacturers to reduce cut outs, and consequently increase installation speed. Interviewee J, who works for an owner company, mentioned that modular construction and prefabrication are heavily implemented mainly due to the remote location of their projects and shortage of housing for the workers. Interviewee D mentioned that his company has a division focused solely on identifying opportunities of applying sustainability strategies on the projects; however, there was not a specific strategy always adopted across every project. Along the same lines, Interviewee L said that he did not believe in "must-do policies", and that there was not a corporate-based structure or guideline that determined the adoption of circular strategies. On the other hand, Interviewee K described a formal document with "green opportunities" available in his company in which each design-build project team was responsible to adopt at least 5 strategies that were suitable for that project – he said: "I'd rather have the teams evaluate the list, engage in what makes sense to them, and drive that implementation, instead of forcing everyone to always adopt one strategy".

Lastly, the interviewees were asked questions about their practices with C&D waste reuse and recycling. One question was whether the interviewees thought there was a market for reclaimed materials/components reuse in the U.S, and what were some existing challenges. In this question, there was almost a consensus among the interviewees that C&D waste reuse, and reclaimed materials reuse, is mainly driven by either a significant financial benefit for the project, or by an owner's specific request. Notably, intra-company surplus materials reuse and sharing of resources were cited as common practices; yet, the purchase of reclaimed materials for reuse was not. Interviewees H and O highlighted that in their experience, most of the reclaimed materials are used in small architectural applications – e.g., reclaimed masonry for specific walls, or reclaimed wood structures – instead of robust uses across the project. The major challenges of reusing reclaimed materials or C&D waste cited were: (1) lack of data about the materials and their conditions; (2) stigma of using "second-hand" products; (3) matching supply and demand in terms of materials quantities and locations, which often makes the process not viable; (4) difficulty in certifying the salvaged materials with the American Society for Testing and Materials (ASTM) standards; and (5) expenses associated with the treatment of these materials in order to enable their reuse (e.g., especial paints and fireproofing treatments, waterproofing systems required).

Unlike reuse, it was observed that C&D waste recycling (specifically open-loop) was a very common and disseminated practice. For instance, Interviewee Q described that her company has a threshold of diverting at least 95% of their project's C&D waste from landfills; additionally, waste generation is tracked on every project of the company. Along the same lines, Interviewee E talked about his previous company, in which there was a threshold of diverting at least 75% of C&D waste from landfills in every project – independent of green certifications. Interviewee I, who works for a consulting firm doing research on CE, also confirmed – "Open-loop recycling is very common, everyone is recycling as much as they can – this is the low-hanging fruit of all sustainability strategies". She continued, "yet, this is the lowest value opportunity, and it's not the point of CE".

4.4.2.2 Circular Strategies Implementation Barriers

Based on the interviews conducted, five groups of barriers for the implementation of circular strategies were identified – they were: (1) budget and upfront costs; (2) schedule and project timeline; (3) lack of awareness and change resistance; (4) current construction business model; and (5) lack of regulations and implementation guidelines. Budget and schedule constraints are common in construction projects. The implementation of certain circular strategies may require upfront costs in order to enable future reuse of materials and components. Furthermore, lack of in-house expertise and necessity to hire external consultants was cited as a potential additional cost. According to some interviewees, certain owners are more susceptible to invest in sustainability and implementation of circular strategies (e.g., tech companies, or large corporations). However, some owners have tighter budget constraints, which may hinder the adoption of the strategies. While schedule-driven projects may leverage the adoption of some circular strategies such as prefabrication and modularization, schedule constraints might affect the owner's willingness to implement other strategies such as selective demolition or deconstruction.

Lack of awareness and knowledge of building circularity were cited as main barriers by nine out of the 17 interviewees. According to Interviewee D, some of the circular strategies are new to the U.S. construction context – which is the case of design for disassembly and design in layers. He mentioned "there have been designers who developed projects for future deconstruction, it has been done. However, those were pilot projects, proofs of concept. I don't think that we have developed the best pattern yet". Besides the lack of awareness, resistance to change is a common characteristic of the construction industry (Lines et al., 2015). According to Interviewee G, construction projects usually have high risk and low profit margins involved, which is a scenario that tends to discourage the adoption of new technologies, and ways of designing. As pointed out by Acharya et al. (2018), the built environment is not conducive to a start-up culture. Interviewee M agreed that resistance to change is a major barrier in the industry – she cited the following widespread mentality – "This is the way we've been doing construction for years, why change?"

The current construction business model was cited as another major challenge for the adoption of circular strategies. Interviewee B explained that the construction developers' business plan does not necessarily follow the same lifespan to which the building is designed. That is, often times, the developer's investment is recovered way before the intended building lifespan, in a manner that stakeholders are less concerned with the end-of-life of the project. On the same subject, Interviewee I pointed out – "sometimes is difficult for the owners or stakeholders to appreciate the need for something that is beyond the period of time that they are thinking about". Rethinking construction business models is necessary to incorporate circularity into the built environment. With a few exceptions (e.g., the lease of carpets and lighting in commercial buildings), the mainstream construction business model is based on the ownership of materials and components for a certain period of time before they reach the end of its useful life and are discarded. Interviewees I and K discussed the potential to apply product as a service (PaaS) types of business model to buildings' facades and steel structures. The application of this type of model would facilitate the reuse of materials and components, as well as recycling once the end-of-life is inevitably reached.

Lastly, seven interviewees cited the lack of regulations and guidelines as major barriers for the implementation of circular strategies. Local regulations play an important role especially when it comes to C&D waste management. Interviewee C cited a project in which the owner requested a "zero waste" jobsite and LEED Platinum certification. According to Interviewee C, this was a special case of owner enforcement, and the project was in a progressive city in the U.S., which has a strong program of incentives for recycling. An example of waste management practice in that project was the collection of jobsite food scraps by the city's composing program – which helped the achievement of the project's goals. Yet, Interviewee C pointed out that local regulations are of paramount importance to enforce sustainable practices in small or medium projects in which the owner is not making any stringent requirements, nor is seeking sustainable certifications. Interviewee O gave a similar example of two projects in his company, one in downtown of a progressive and fast-growing city in the U.S., and one in a suburban of the same city. The downtown project had to comply with the city's green building rating system, and all C&D waste data needs to be tracked and reported. The suburban project did not have the same regulations, and the owner did not have any specific requirements towards C&D waste management. As such, C&D waste data was not being tracked in that project – Interviewee O explained, "From a contractor's perspective, there is no economic reason to track it. It just costs money, and there's no financial incentive." In sum, there is a disparity between regions in the U.S. in terms of building regulations and guidelines. In places where the regulation is less stringent and environmentally conscious, the industry relies on educated clients and clients who are willing to take risks and spend more on the implementation of circular strategies. According to Interviewee I, the majority of the work that has been done in the U.S. in terms of CE was driven from the East and West coast regions of the country.

4.4.2.3 Circular Economy Enablers

The last interview topic was the enabling factors for a transition towards a CE model in the built environment in the U.S. The interviewees answers were summarized in four main groups: (1) education and cultural change; (2) data availability; (3) policies and market-based incentives; and (4) popularization of new voluntary stewardship programs. Bringing awareness to the detriment caused by the construction industry's linear economic model was cited as a first-step to enable the adoption of a CE model in the built environment. According to Interviewees E, I, and L, it will be hard to shift the industry if the public sector and AEC stakeholders do not understand CE and its value. Notably, Interviewee L highlighted the importance of understanding the difference between a CE model and traditional sustainability thinking. The CE model is intrinsically related to the idea of an economic gain or an opportunity, and something that is financially viable. Whereas more traditional sustainability thinking may place less emphasis on the financial aspect of businesses – which might discourage its wide adoption. Additionally, the interviewees cited the need for a cultural change and a shift from short-term thinking to long-term thinking when it comes to natural resources and its availability.

Construction has a complex and decentralized supply chain. As such, collecting data for embodied carbon lifecycle assessments can become challenging. One enabler for the adoption of a CE model in the built environment is access to transparent data in order to make more informed decisions. One example is through the use of the Health Product Declaration® (HPD) Open Standard; which is a standard specification for the consistent report of building materials and products' contents and health information (HPD Collaborative, 2021). Notably, the HPD standard complies with different building certification programs (e.g., LEED, WELL) and can be used to help achieve these certifications (HPD Collaborative, 2021). Additionally, due to the complexity of construction projects, Interviewee K suggested focusing on the circularity of few scopes of work and materials at a time – as opposed to thinking holistically about the circularity of the entire building. According to him, leveraging data and tracking specific scopes of work (e.g., steel, concrete, drywall and framing) might facilitate gradual changes in the industry.

Policies and financial incentives, or disincentives, such as carbon taxes or landfill bans, were cited by eight interviewees as enabling factors for a more circular and environmentally conscious built environment. Notably, great part of the interviewees mentioned that the public and private sectors need to collaborate in this realm. According to Interviewee E, a collaborative setting between private AEC stakeholders and the public sector is necessary to define reasonable and acceptable requirements, and to define realistic short-term and long-term goals. Lastly, the popularization of new voluntary stewardships programs with focus on building circularity was cited as a potential enabler for a transition into the CE model. Throughout the years, the LEED scheme gained popularity and fostered improvements in the design of buildings; additionally, it became a brand to which companies and organizations like to have their name associated with, and are willing to pay a premium for that. For some interviewees, the creation of new stewardship programs that are valued by the market, and that focuses on the circularity of building materials and components would increase the visibility and importance to the topic.

4.5 DISCUSSIONS

Literature about CE for the U.S. built environment is lagging behind from other countries in Europe and Asia. Different reasons may be possible for this lag, a report published by the One Planet Network (OPN) (2020) suggests that the extensive land and resources availability in the U.S. make the shift away from a linear economy less enticing when compared to countries in Europe or Japan – which have limited resources. Nonetheless, CE is gaining traction and its potential economic and environmental gains, for both developed and developing countries, are being largely discussed (WBCSD, 2018; WEF, 2016; ING Economic Department, 2015). Environmental gains of a transition towards a circular built environment include: (1) ease the burden on global ecosystems and resource consumption (EEA, 2016); (2) reduction of greenhouse gas emissions (EEA, 2020); and (3) reduction of C&D waste generation (Ruiz et al., 2020). Furthermore, economic gains of this transition concentrate around: (1) resource productivity (Ruiz et al., 2020); (2) mitigation of demand-driven materials price volatility and supply risks (WEF, 2014); (3) savings associated to environmental and public health externalities (WBCSD, 2018); and (4) employment creation (Morgan and Mitchell, 2015). Notably, an increasing number of companies in the construction sector already started to invest in new technologies, big data, and business models that leverage circularity in the built environment (Rizos et al., 2016; OPN, 2020) – examples include the use of AI and robotics to sort construction waste (AMP Robotics, 2021; Zabble Inc, 2021), PaaS business model (Philips Lighting, 2021; Tarkett, 2021), and modular construction for disassembly (Blokable, 2021; Sustainable Living Innovations, 2021). Moreover, an increasing number of successful circular construction case studies are becoming available in the literature (EMF, 2016b; BITC, 2020; Zimmann et al., 2016).

Despite the increased attention to the CE model and the aforementioned benefits, several challenges are still present when it comes to a transition towards a CE in the built environment. According to the participants of this study, the most significant challenges identified are related to budget and upfront costs, lack of awareness and CE education, lack of policies, and changes required in current construction business models. Lack of capital and upfront costs is a barrier largely cited in the literature, and such barrier is especially evident in small and medium-sized enterprises (Rizos et al., 2016; Trianni and Cango, 2012; Kirchherr et al., 2018). The upfront cost barrier is also tied to a lack of in-house technical and technological know-how, which further challenges the transition from linear to circular business models (van Eijk, 2015). Education and understanding of CE benefits is another popular barrier cited by different authors in the literature (Rizos et al., 2016; Kirchherr et al., 2018; Acharya et al., 2018). Notably, while lack of CE knowledge is a barrier, good awareness of CE alone does not necessarily translate into a company's willingness to adopt CE principles, as demonstrated by Liu and Bai (2014) and Kirchherr et al. (2018). Along with CE awareness, market conditions such as consumer demand and economic attractiveness are necessary for a transition towards circularity (Gue et al., 2020; Rizos et al., 2016; Kirchherr et al., 2018). One market condition that may represent a barrier towards circularity is the lower price of virgin materials when compared to recycled materials (Mont et al., 2017). Finally, regulatory barriers is another highly discussed theme in the CE literature (de Jesus and Mendonça, 2018; Acharya et al., 2018). Specifically to the U.S. context, it is recognized the lack of consistency in environmental regulations at the city, state, and federal levels (OPN, 2020; Ranta et al., 2018) – e.g., states like California, Colorado, and Washington have higher environmental consciousness and more initiatives to address built environment issues than other states (OPN, 2020). As such, some cities and states are more inclined to advance towards circularity than others. Notably, additional challenges may be encountered in the path towards circularity in the U.S. built environment – examples include adaptation of current construction design codes, budget shortages, and political aspects.

Nevertheless, the construction industry in countries with similar levels of industrialization to the U.S. already started to implement different CE principles into their built environment. As expected, such transition towards circularity is not straightforward, nor a "one size fits all". Each country should identify the barriers and drivers of implementing a CE in their own context, as well as develop strategies and roadmaps to accelerate the implementation path. Notably, multi-stakeholder engagement (i.e., government, businesses, academia), and exchange and dissemination of knowledge are key to push forward the adoption of a CE model in the built environment – these points were highlighted by this study's interviewees, and are also recommended in the literature (OPN, 2020; Rizos et al., 2016; Acharya et al., 2018). A multi-stakeholder engagement would facilitate developing a CE roadmap, as well as identifying necessary amendments to policies and existing building codes (OPN, 2020). One example of engagement is through public-private partnership projects, which would foster the development of scalable circular projects (Acharya et al., 2018). New voluntary stewardship programs focusing on building circularity was another enabler suggested by this study's participants that is also highlighted in the literature. According to UN's International Resource Panel (IRP) (2020), building certification systems are a strong tool to influence design and construction – this is especially true when governments integrate certification systems into design and construction codes. Such integration could be a first-step and would be especially beneficial for U.S. cities that currently do not have environmentally conscious regulations in place. Finally, it is expected that the transition towards circularity should be led by stakeholders with the greatest capacity to influence decision-making; specifically, these are: (1) policymakers; (2) investors; and (3) construction clients (Acharya et al., 2018).

4.6 CONCLUSIONS

As environmental issues and resource scarcity risks are becoming more evident, there is an increase in policies and roadmaps promoting a transition towards a more resource efficient and circular built environment (OECD, 2018). The study presented in this chapter assessed U.S. AEC industry stakeholders' awareness of CE in the built environment, as well as, the major barriers of adopting circular strategies in construction projects, and enablers for a transition into a CE model. 130 online survey results and more than 14 hours of interviews with AEC stakeholders of four different regions of the U.S. (i.e., West, Southwest, Southeast, and Northeast) were collected and analyzed. Notably, one limitation of this study is the possibility of inaccuracy in the circular strategies' awareness reported by the survey participants. In fact, the levels of awareness reported may be higher than the reality; this is mainly due to the Socially Desirable Responding (SDR) phenomenon, which is defined as a tendency to give positive and desirable self-descriptions and assessments (Paulhus, 2002). Furthermore, it is important to acknowledge a possible bias due to the interviewees' demographics (i.e., majority of middle-aged, male participants). Additionally, while the number of participants in this study was within the recommended for qualitative research (specifically phenomenological studies), and was comparable to other studies in the same field, more insights and further barriers could have been identified with additional survey responses and interviews. Due to the extension of the U.S., future work should include replicating this study but focusing on smaller geographic regions (e.g., a study focusing only on U.S. West coast AEC industry stakeholders). Such studies would enable identifying differences between the participants' perception of barriers and enablers according to their geographic regions, as well as better understanding corporate culture differences. Moreover, studies focusing on smaller geographic regions would enable depicting the differences in the state of adoption of circular strategies across the U.S. Another path for future works include identifying the necessary adaptations in current U.S. construction design codes in order to incorporate the major circular strategies identified in this study. In summary, this chapter provided an overview of the state of practice of major circular strategies adoption in the U.S., pinpointing existing barriers. Furthermore, it assessed U.S. AEC industry stakeholders' perceptions of enabling factors for a transition towards a CE model in the construction industry. Findings presented in this chapter can aid the development of frameworks for applying CE concepts in the built environment in the U.S.

Chapter 5: Conclusions

C&D waste generation and resource recovery are current major challenges for the construction industry. This is mainly due to the increasing volume of waste produced worldwide, resource scarcity issues, and serious associated environmental impacts (Ruiz et al., 2020). Notably, C&D waste is given attention by different policies at the global level – e.g., the Waste Framework Directive in the European Union (European Commission, 2019), the Implementation Plan of Predominant Resource Recycling Project in China (Huang et al., 2018), and the Basic Law for Establishing the Recycling-based Society in Japan (Environment Agency Japan, 2000). Additionally, transitioning towards a CE has been proposed as a solution for the C&D waste generation and resource recovery issues, and several cities around the globe started to implement circular initiatives – e.g., Amsterdam (Netherlands); Austin, New York City, San Francisco (U.S.); Glasgow (Scotland), among others (Ellen MacArthur Foundation, 2019).

The research presented in this dissertation focused on CW management and resource recovery issues throughout a construction project lifecycle. Specifically, Research Question 1 focused on streamlining CW generation estimation during early stages of the project, Research Question 2 focused on enhancing and formalizing CW R&R planning during construction of the project, and Research Question 3 focused on the challenges and enablers for the implementation of strategies aligned to a CE model in the end-of-life of the construction project, and in the design of new construction projects in the U.S. The following sections summarize the contributions of each research question, as well as the limitations and future works associated with them.

5.1 CONSTRUCTION WASTE ESTIMATION

Estimating overall CW generation accurately is the first step to enable the implementation of an effective an actionable CWMP at the project level. While several CW generation estimation methodologies were available in the literature, gaps still remained. A literature review (provided in Chapter 2) revealed major challenges such as time-consuming methodologies, lack of granularity in the estimate, reliance on macro-level parameters (e.g., national building permits, population growth, construction activity of a certain area) or on data that is not commonly available in construction projects (e.g., waste generation rates from the geographic region of the project). Furthermore, often times, the fast-pace of construction projects itself represents a challenge for implementation of CWM techniques – especially in projects where sustainability is not emphasized.

The specific Research Question 1 is "How can construction waste generation *estimation be streamlined* by leveraging BIM data during the early phases of a project?" Notably, the major contribution of Research Question 1 is providing a **straightforward** CW generation estimation methodology that can be easily implemented at the project-level. The methodology demonstrated is based on linear equations and relies on data **commonly available** and **easily accessible** in construction projects (i.e., materials purchasing records). Furthermore, it leverages BIM for a more automated, efficient, and reliable materials' QTO – thus, eliminating the need for manual computations. In sum, **streamlining CW generation** estimation at the project level provides a **foundation** for project teams to implement other CWM techniques, such as R&R planning. Moreover, it soothes the barrier of seeing CWM as a secondary objective in projects in which green certifications are not being sought.

5.1.1 Limitations and Future Works

The algorithms presented in Research Question 1 focused on **concrete** and **drywall** waste streams – which are among the largest waste streams in building construction in the U.S. Nonetheless, other major waste streams are common in construction projects (e.g., wood, steel, tiles, cardboard, masonry). Moreover, the representativeness of a specific waste stream varies according to the type of construction and geographic location of the project – e.g., masonry is a major waste stream in building construction in Brazil, while drywall waste is not very common. As such, future work should include the development of other algorithms that consider the specificities of each waste stream, and allow their generation estimation.

The methodology proposed in Research Question 1 does not use any external data other than BIM and materials purchasing records. In this study, the proposed algorithms were demonstrated in an institutional building complex pilot project, and the results were validated with actual data (i.e., ground truth data from waste hauling tickets) and literature values. Future work should include applying the proposed algorithms in **different types of projects** (e.g., residential, industrial, commercial) to further validate its usefulness. Expanding the application of the proposed algorithms to other types of projects, and validating the results with actual CW data, would help build trust and evidence of the benefits of using BIM for CW generation estimation.

Lastly, the algorithms demonstrated in this research use BIM for materials' QTO. While using BIM for materials' QTO already represents a gain of time, accuracy, and reduction of errors, **further automation** could be achieved in the algorithms presented. For instance, the computations to reduce the rebar volumes of the structural elements in the concrete algorithm could be automated. Specifically, the use of **generative design tools** provide an opportunity to automate such computations and, thus increase convenience for project teams in estimating CW generation.

5.2 Construction Waste Reuse and Recycle Planning

A literature review provided in Chapter 3 revealed that despite being the least desirable option in the 3R's waste management principle, CW recycling is a practice more widely adopted then CW reuse. Notably, it is common that the planning of **CW R&R** at the project level does not follow a formal process and is rather performed **ad-hoc**. This is especially true when sustainability is not a primary goal in construction projects, and the reasoning behind this is the disregard to CW R&R planning methodologies that are time-consuming or convoluted. As a result of such informal planning, opportunities for better resource recovery are not leveraged, and CW that is sent to off-site recycling could have been reused on-site – or even worst, much CW end up in landfills rather than being reused or recycled. As such, the specific question addressed in Research Question 2 is "How can construction waste reuse and recycle planning be *enhanced and formalized* during the construction phase of a project?"

In Research Question 2, a methodology to **formalize CW R&R planning** is demonstrated, leveraging 4D-BIM technology. The main contributions of the proposed methodology is that through the use of 4D-BIM, planning is enhanced, and users are able to **visualize** CW generation as construction progresses, as well as **plan in advance** for on-site CW reuse opportunities. Therefore, minimizing the amount of waste that is sent for recycling, or directed to landfills. With the CW R&R planning methodology demonstrated in Research Question 2, project teams are able to rely on BIM to estimate CW quantities for R&R thus avoiding manual computations. Notably, the methodology was demonstrated with two real-world case studies, and the CW R&R estimates were validated with real-world data (i.e., ground truth data from waste hauling tickets), and literature values using two different approaches (i.e., percentage of material wasted, and waste generation rates). In sum, the main contribution of the methodology presented is promoting a **schedule-based** and more **proactive CWMP**, which contrasts with the often times overly generic document adopted in construction projects.

5.2.1 Limitations and Future Works

One limitation of the CW R&R planning methodology proposed is that it focuses only on **direct waste**; that is, waste generated during transportation or other types of indirect waste, such as rework, are not considered. Future work should address this limitation. Moreover, future work should focus on including more details in the CW R&R planning **4D simulation** to make it more realistic – i.e., materials transportation and large equipment such as cranes should be included.

The work presented in Research Question 2 is a stand-alone 4D simulation showing CW generation, and separation of CW for on-site reuse and off-site recycling. While this is already a visual and formal CW R&R planning methodology, further **integration** with other construction **software systems** could be achieved to formalize and enhance CWM even further. One example is to integrate the 4D simulation with the project's **scheduling** software. The idea behind such integration is that when an opportunity for on-site CW reuse is detected, an activity is automatically created in the project's schedule – thus, notifying the project team to store the CW generated for later reuse on a specific activity. Another example is to automatically create an activity in the project's schedule once it is estimated that site dumpsters achieved their maximum capacity – thus, notifying the project team when it is time to call the CW disposal company.

Similarly to Research Question 1, the methodology proposed in Research Question 2 also focused on **concrete** and **drywall** waste streams. Notably, in order to develop a more comprehensive and robust CW R&R planning framework it is necessary to consider all major CW streams being generated on the project and their **interdependencies**. It is worthwhile to mention that some waste streams are more challenging than others in terms of R&R planning; this is the case of **wood waste** generated from formwork activity. While wood waste is also considerable in construction projects in the U.S., different and more subjective assumptions are needed in order to estimate and plan its R&R with some accuracy. Examples of assumptions include: (1) the number of times the formwork is usually reused before being discarded; (2) the architecture of the project which may difficult material reuse; and (3) on-site handling practices which may compromise the material's properties and integrity, and thus, reuse.

5.3 Circular Economy in the Built Environment in the United States

There has been an increase in policies and roadmaps propelling the shift towards a more resource efficient and CE in recent years. While the CE concept is gaining traction, literature focusing in CE for the **construction sector** is still in its infancy, and the majority of publications available are from European and Asian countries. Moreover, given that CE for the construction sector is still a relatively recent concept, one of the most popular group of studies focuses on assessing construction stakeholders' **awareness** and knowledge of the concept; as well as, understanding **barriers** and **opportunities** for the transition towards a CE model in the built environment. While this set of studies are popular, as demonstrated in the literature review provided in Chapter 4, no study has yet been published with such focus for the **U.S. AEC industry context**. Therefore, the specific question outlined for Research Question 3 is "What is the state of practice of Circular Economy in the United States building construction industry?"

Notably, the main contribution of Research Question 3 is thus filling this gap in the literature, by assessing U.S. AEC industry stakeholders' level of awareness in CE, and pinpointing major barriers and enablers of adopting sustainable strategies. This study provides a better understanding of the **current level** of adoption of CE concepts and principles in the construction sector in the U.S. Specific contributions of Research Question 3 include pinpointing the **most disseminated** circular strategies (i.e., open-loop recycling, selective demolition, and prefabrication), and the ones that are **hardly adopted** (i.e., design for disassembly, design in layers, closed-loop recycling) in construction projects in the U.S. Additionally, findings of this study pinpointed five **major barriers** (i.e., budget and upfront costs, schedule and project timeline, lack of awareness and change resistance, current construction business model, and lack of regulations and implementation guidelines) and four **enabling factors** (i.e., education and cultural change, data availability, policies and market-based incentives, and popularization of new voluntary stewardship programs) for a shift towards a CE model in the built environment in the U.S.

In sum, the aforementioned results document the current state of sustainable construction in the U.S. and serve as a **stepping stone** for future studies. Moreover, understanding the **current state** of sustainable construction is a necessary step in the development of roadmaps and guidelines for a CE transition in the built environment.

5.3.1 Limitations and Future Works

While the number of participants in Research Question 3 was within the recommended for qualitative research, and was comparable to other studies in the same field, more insights could have been achieved with more survey responses and interviews. Notably, one way to overcome such limitation is with future studies that focus on smaller geographic regions in the U.S. (e.g., Southwest, Southeast, West, Midwest, Northeast). Studies focusing on smaller geographic regions may indicate more clear regional differences in the adoption of circular strategies, as well as differences in barriers and enablers perceived by the participants. Better understanding such differences between geographic regions in the U.S. may aid developing more actionable roadmaps and guidelines for a CE transition in the built environment.

Due to the limited body of knowledge focusing on CE in the construction sector in the U.S., various paths of future works are available. One interesting path would be to better understand the current **policies** and **regulations** in place in the U.S. and evaluate gaps on how they support the implementation of a CE in the built environment. Another path would be, based on the aforementioned regional studies, propose **roadmaps** for the implementation of a CE in the built environment in the U.S.

Appendix A – Abbreviations List

Appendix A contains a list of abbreviations used throughout this dissertation:

AEC – Architectural, Engineering, and Construction

AI – Artificial Intelligence

ANOVA – Analysis of Variance

BIM – Building Information Modeling

C&D – Construction and Demolition

CE – Circular Economy

CMU – Concrete Masonry Units

CSA – Classification System Accumulation

CW – Construction Waste

CWM – Construction Waste Management

CWMP – Construction Waste Management Plan

GRC – Generation Rate Calculation

LA – Lifetime Analysis

LEED – Leadership in Energy and Environment Design

LOD – Level of Development

QTO – Quantity takeoff

R&R – Reuse and Recycling

RFID – Radio Frequency Identification

RQ – Research Question

SV – Site Visit

VM – Variables Modeling

Appendix B – List of 3D Model Requirements

Appendix B summarizes the 3D model requirements in place related to Research Questions 1 and 2 of this dissertation, which are presented in Chapters 2 and 3, respectively.

B.1 Level of Development (LOD) of the 3D Model

According to AIA the Level of Development (LOD) describes the level of completeness to which a Model Element is developed. For the use of the algorithms presented in Research Questions 1 and 2 it is recommended a model with at least LOD 300. That is, a model with accurate assemblies in terms of quantity and shape.

B.2 3D Model Requirements for Concrete algorithm

When inserting "Columns", "Structural Columns" "Floor", "Beams" (or structural framing), "Piles" (or structural foundation) and "Stairs" in the model, make sure to edit the "Type Properties" and fill the "Materials and Finishes" parameter with a type of material that contains "Concrete" on the name. If the concrete element does not have this parameter defined and set this way, the element will not be quantified.

2.1) Properties Set-up Demonstration in Autodesk Revit

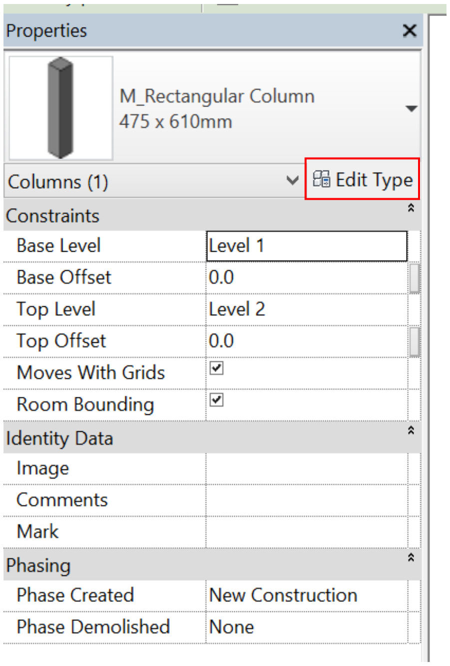


Figure B-1: Select the structural element and click "Edit Type"

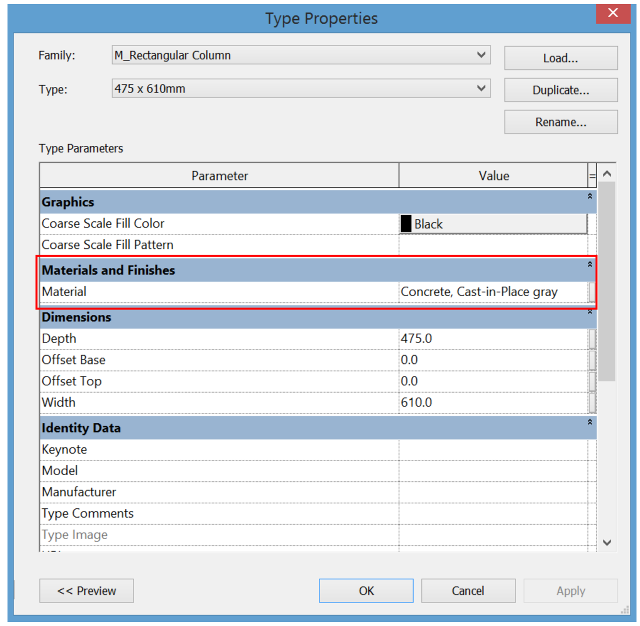


Figure B-2: Make sure the "Materials and Finishes" has "Concrete" on its name

B.3 3D Model Requirements for Drywall algorithm

When inserting "Walls" on the project make sure that whatever wall that has drywall should contain on its "Type Properties" under "Core Boundary" > "Finish" a material that contains the word "Gypsum". If the wall element does not have this parameter defined and set this way, the element won't be quantified.

3.1) Properties Set-up Demonstration in Autodesk Revit

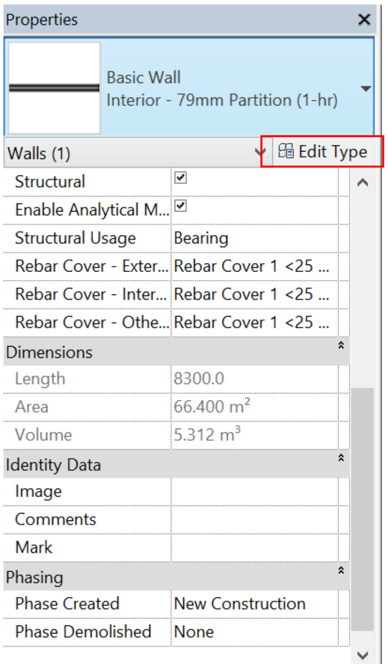


Figure B-3: Select the Wall and click "Edit Type"

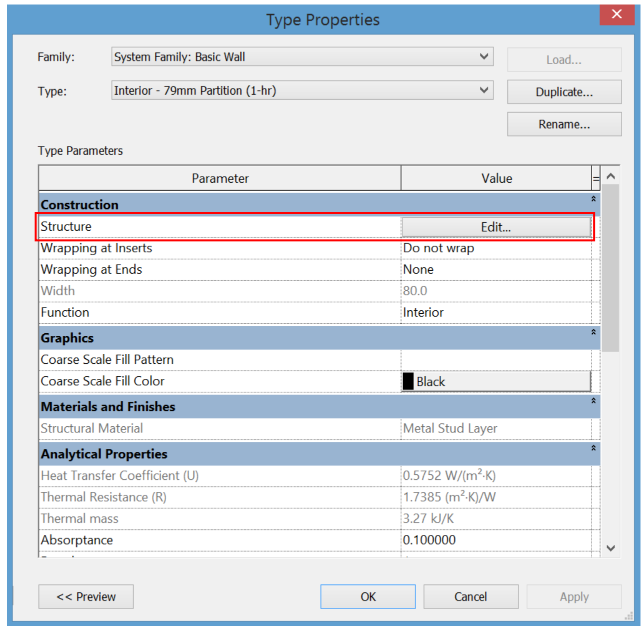


Figure B-4: Edit the "Structure" property of the Wall

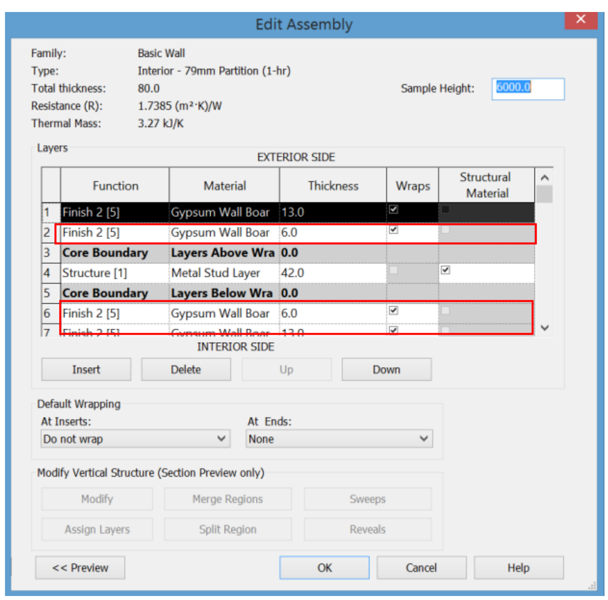


Figure B-5: Make sure the "Finish" has "Gypsum" on its name

Appendix C – Quantity Takeoff Demonstration

The screenshots below demonstrate how to perform concrete and drywall Quantity Takeoffs using Autodesk Revit 2016. This demonstration refers to Research Question 1 of this dissertation, presented in Chapter 2.

C.1 Concrete Quantity Takeoff Demonstration in Autodesk Revit

The step-by-step on retrieving concrete data using Revit's function "Material Takeoff" is demonstrated on the figures below. Foundation piles were the structural elements selected to demonstrate the concrete part of the algorithm, and the structural model of the building was the one used to retrieve the data.

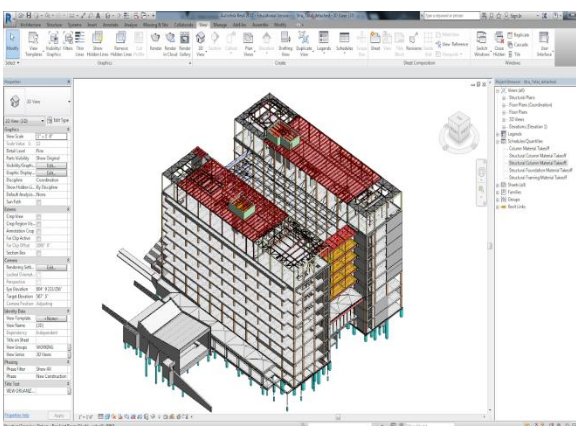


Figure C-1: Revit structural model initial interface

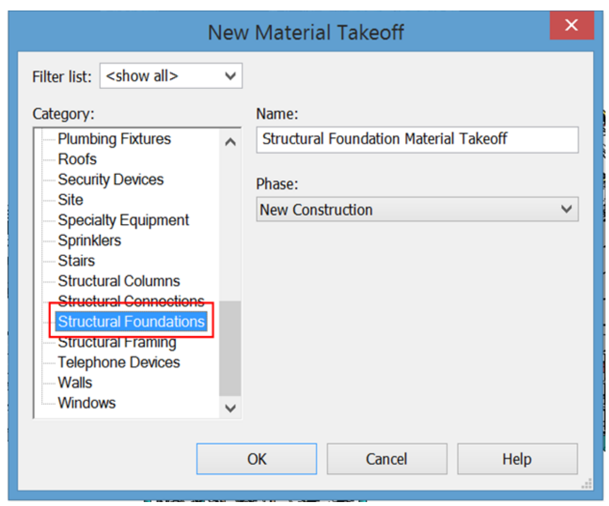


Figure C-2: Revit Schedule Material Takeoff for "Structural Foundations"

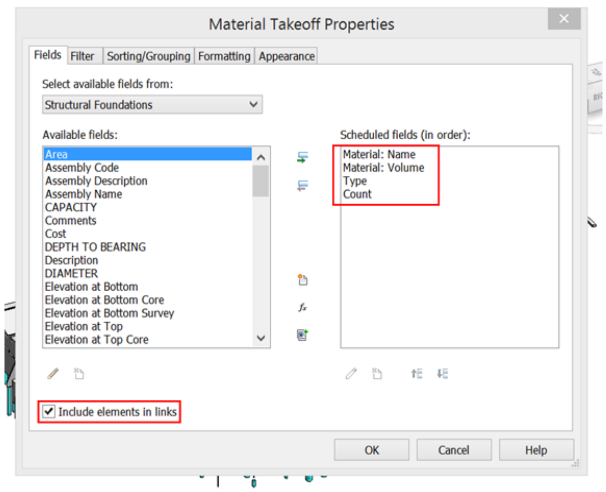


Figure C-3: Scheduled fields of interest (Material: Name, Material: Volume, Type and Count)

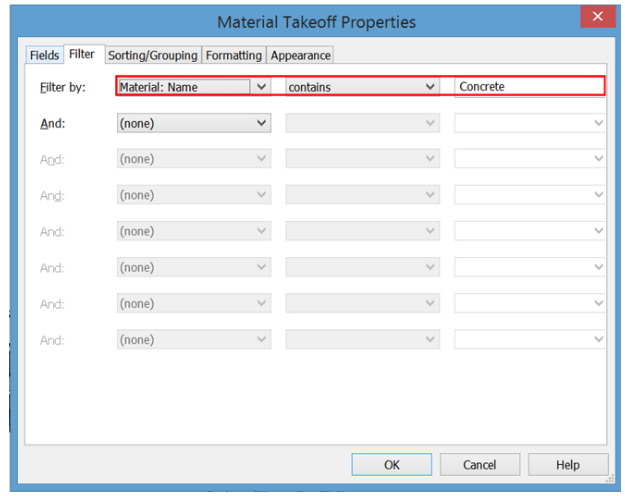


Figure C-4: Filtering piles by "Material: Name" that contains "Concrete"

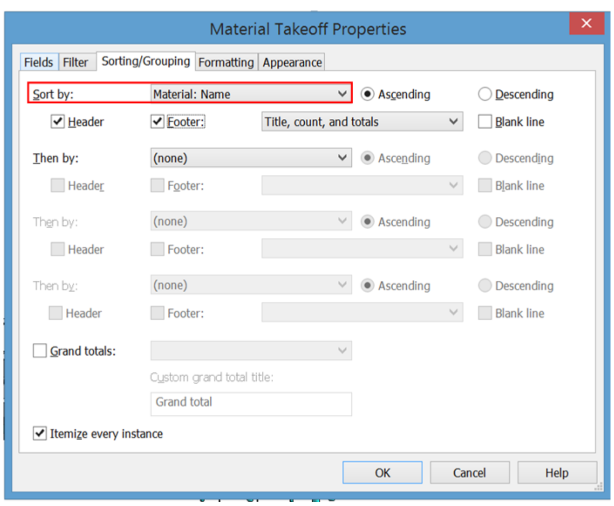


Figure C-5: Sorting the piles by "Material: Name"

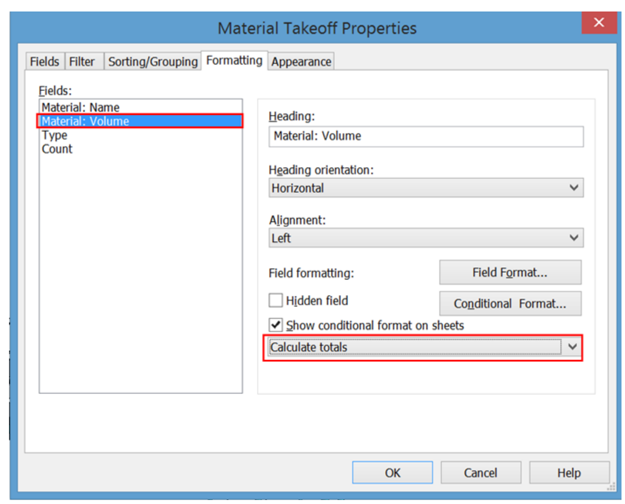
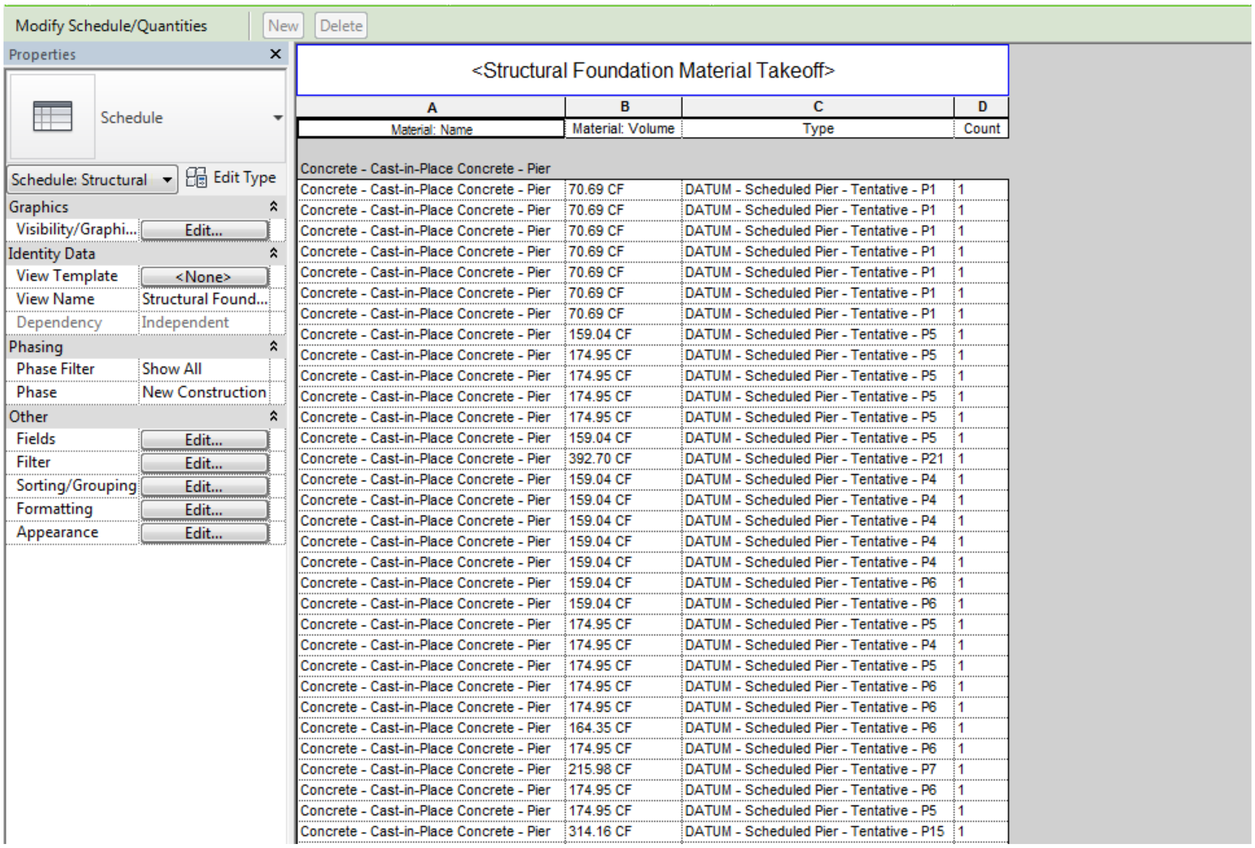


Figure C-6: Setting Revit to calculate volume totals

The list of the project's piles ("Structural Foundations") and their volumes as defined on the previous set ups is shown on Figure C-7.



A	B	C	D
Material: Name	Material: Volume	Type	Count
Concrete - Cast-in-Place Concrete - Pier			
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	70.69 CF	DATUM - Scheduled Pier - Tentative - P1	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	392.70 CF	DATUM - Scheduled Pier - Tentative - P21	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P4	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P4	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P4	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P4	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P4	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	159.04 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P4	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	164.35 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	215.98 CF	DATUM - Scheduled Pier - Tentative - P7	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P6	1
Concrete - Cast-in-Place Concrete - Pier	174.95 CF	DATUM - Scheduled Pier - Tentative - P5	1
Concrete - Cast-in-Place Concrete - Pier	314.16 CF	DATUM - Scheduled Pier - Tentative - P15	1

Figure C-7: Structural Foundation Material Takeoff on Revit

The same procedure is performed for the remaining structural elements (i.e., columns, beams, slabs and stairs) changing the "Category" on Figure C-2.

C.2 DRYWALL QUANTITY TAKEOFF DEMONSTRATION IN AUTODESK REVIT

The step-by-step on retrieving the drywall data using Revit's function "Material Takeoff" is demonstrated on the figures below. Walls are the category selected, and the architectural model of the building was the one used.

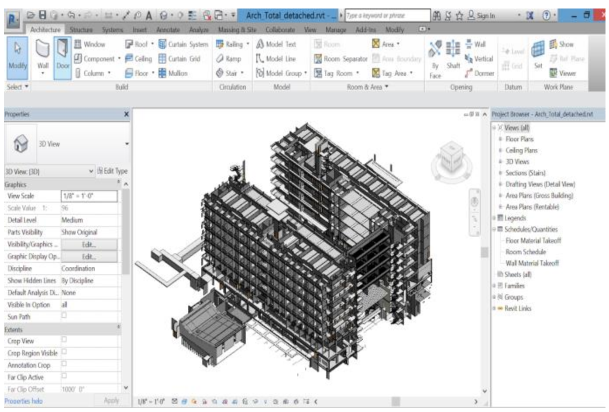


Figure C-8: Revit architectural model initial interface

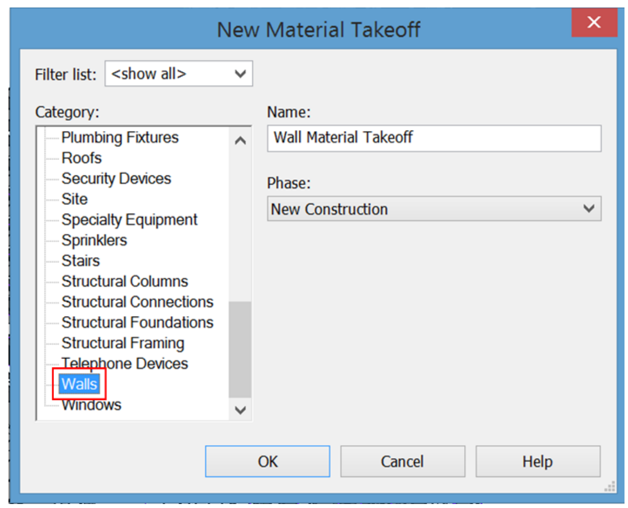


Figure C-9: Revit Schedule Material Takeoff for “Walls”

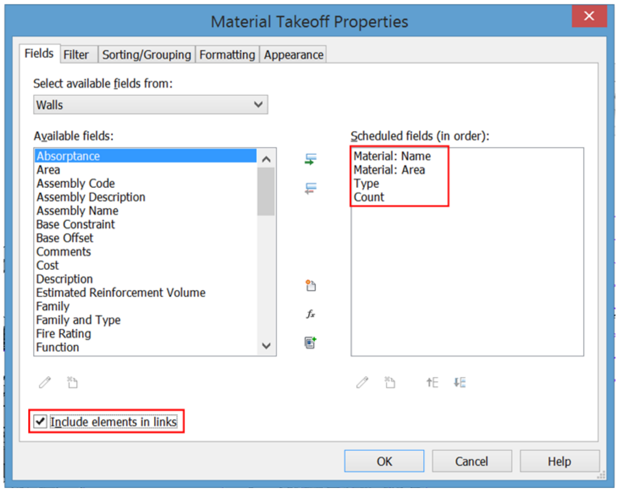


Figure C-10: Scheduled fields of interest (Material: Name, Material: Area, Type and Count)

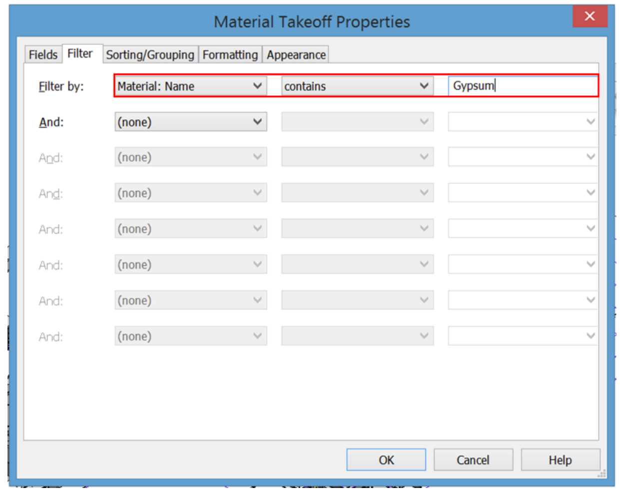


Figure C-11: Filtering walls by "Material:Name" that contains "Gypsum"

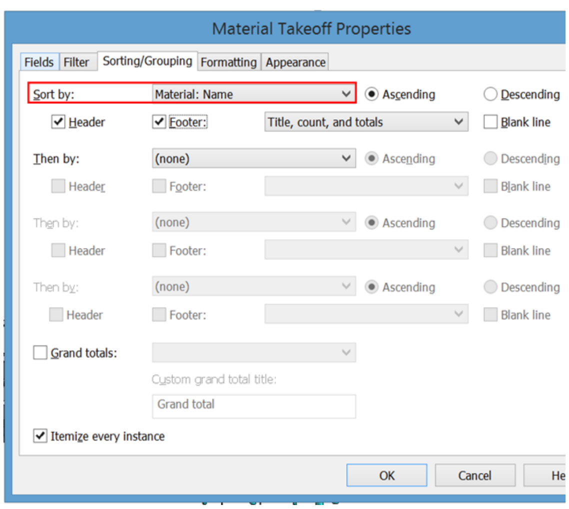


Figure C-12: Sorting the walls by "Material: Name"

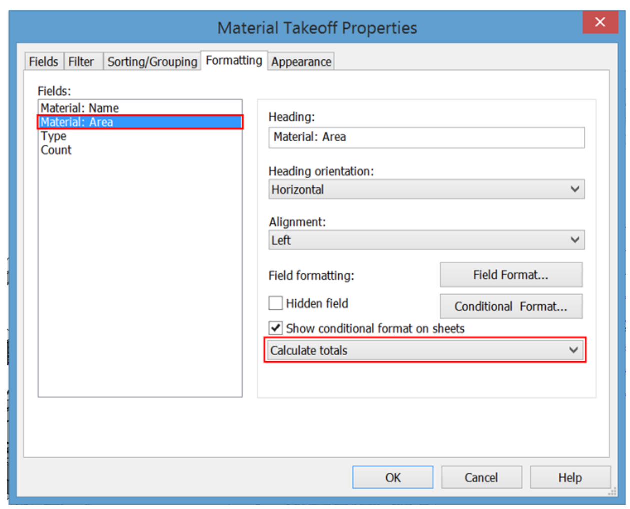
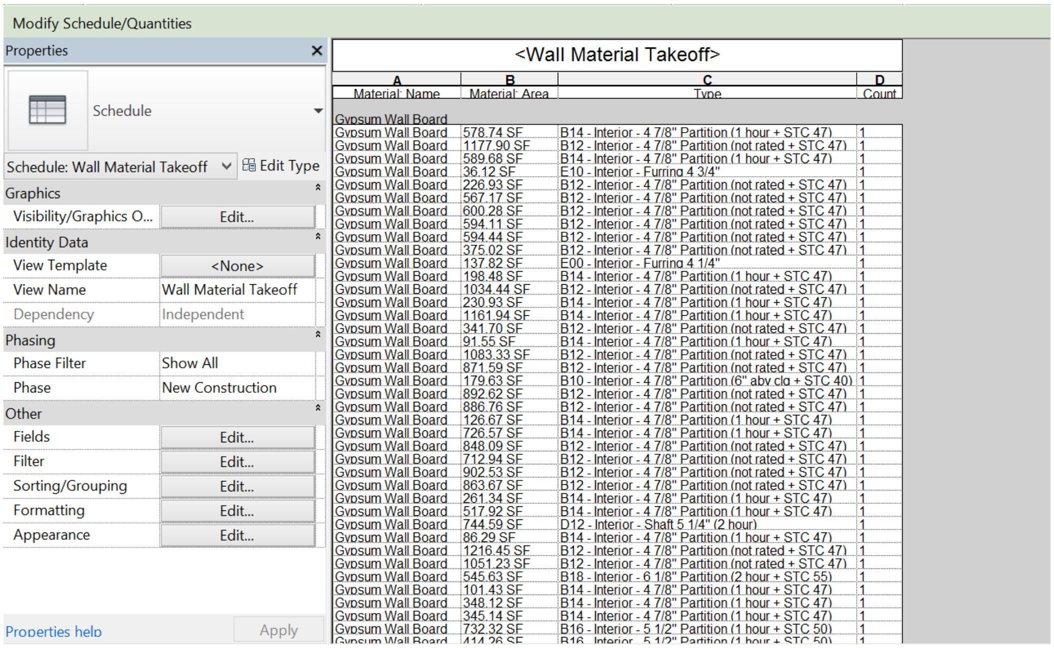


Figure C-13: Setting Revit to calculate total areas of drywall for the walls

The list of the project's Drywall (gypsum board) walls and their areas as defined on the previous set ups is shown on Figure C-14.



<Wall Material Takeoff>

A	B	C	D
Material: Name	Material: Area	Type	Count
Gypsum Wall Board			
Gypsum Wall Board	578.74 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	1177.90 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	589.68 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	36.12 SF	E10 - Interior - Furring 4 3/4"	1
Gypsum Wall Board	226.93 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	567.17 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	600.28 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	594.11 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	594.44 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	375.02 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	137.82 SF	E00 - Interior - Furring 4 1/4"	1
Gypsum Wall Board	198.48 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	1034.44 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	230.93 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	1161.94 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	341.70 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	91.55 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	1083.33 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	871.59 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	179.63 SF	B10 - Interior - 4 7/8" Partition (6" abv clg + STC 40)	1
Gypsum Wall Board	892.62 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	886.76 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	126.67 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	726.57 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	848.09 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	712.94 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	902.53 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	863.67 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	261.34 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	517.92 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	744.59 SF	D12 - Interior - Shaft 5 1/4" (2 hour)	1
Gypsum Wall Board	86.29 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	1216.45 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	1051.23 SF	B12 - Interior - 4 7/8" Partition (not rated + STC 47)	1
Gypsum Wall Board	545.63 SF	B18 - Interior - 6 1/8" Partition (2 hour + STC 55)	1
Gypsum Wall Board	101.43 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	348.12 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	345.14 SF	B14 - Interior - 4 7/8" Partition (1 hour + STC 47)	1
Gypsum Wall Board	732.32 SF	B16 - Interior - 5 1/2" Partition (1 hour + STC 50)	1
Gypsum Wall Board	414.26 SF	B16 - Interior - 5 1/2" Partition (1 hour + STC 50)	1

Figure C-14: Wall Material Takeoff on Revit

Appendix D – Guidelines for 4D Model Development

Appendix D summarizes guidelines for the development of a 4D simulation for CW R&R planning, as presented in Research Question 2 (Chapter 3). Notably, two pieces of information are essential to develop a 4D-BIM: (1) the construction schedule containing the activities that will be performed in the project*;* and (2) the building 3D models. The following subsections describe the data preparation and assumptions made for the development of the 4D simulation of Case Study A, presented in Chapter 3.

Refer to the link below to watch the 4D simulation of Case Study A: https://www.youtube.com/watch?v=S4vZLscgvNc

D.1 CONSTRUCTION SCHEDULE AND 3D MODELS ADJUSTMENTS

The first step to develop a 4D simulation consists in analyzing and adjusting the construction schedule and 3D models. The construction schedule of Case Study A was developed with Primavera P6; and contained all activities from preconstruction, demolition, building construction, and post-construction phases. Since the scope of Research Question 2 is CW, activities from the demolition phase were not considered neither included in the simulation. Furthermore, the granularity of several activities in the construction schedule were adjusted for the simulation development. For instance, the construction of one slab in the original schedule was comprised of many activities (as shown in Figure D-1). Yet, not all these activities were necessary for the demonstration of waste generation. Therefore these activities were merged into four main ones: (1) formwork build; (2) steel placement; (3) concrete pour; and (4) formwork strip. Activities such as “Install Rebar at ESL 1-2 South Tower”, “Install Embeds / Sleeves at ESL 1-2 South Tower” and “Clean and prep slab at ESL 1-2 South Tower” were considered as one “Steel Placement at the 1-2 South Tower” with a starting date of December 12th and a finish date of December 18th. Such pattern was adopted for all elements of the superstructure of the building (i.e., foundation piles, beams, columns, slabs, and stairs).

102-556-02-18.CONST.4.1.2 Elevated Slabs	11-Nov-15	22-Jun-16	158
102-556-02-18.CONST.4.1.2.2 Level 1 South Tower	11-Nov-15	05-Feb-16	61
102-556-02-18.CONST.4.1.2.2.1 ESL 1-2 South Tower	11-Nov-15	02-Jan-16	36
Deck Cure LVL1 Area 2 (STW)	18-Dec-15	20-Dec-15	3
Strip Deck LVL 1 & Re-shore LVL0-1 Area 2 (STW)	11-Nov-15	17-Dec-15	5
Remove Re-shores LVL0-1 Area 2 (STW)	30-Dec-15	02-Jan-16	3
INSTALL SHORING TOWERS AND DECKING AT ESL 1-2 SOUTH TOWER	11-Nov-15	17-Dec-15	4
INSTALL EDGE FORMING AT ESL 1-2 SOUTH TOWER	16-Dec-15	18-Dec-15	5
INSTALL PANS AND FORM BEAMS AT ESL 1-2 SOUTH TOWER	21-Nov-15	18-Dec-15	4
INSTALL REBAR AT ESL 1-2 SOUTH TOWER	12-Dec-15	18-Dec-15	4
INSTALL EMBEDS / SLEEVES AT ESL 1-2 SOUTH TOWER	30-Nov-15	18-Dec-15	5
CLEAN AND PREP SLAB AT ESL 1-2 SOUTH TOWER	15-Dec-15	18-Dec-15	2
DATUM / THIRD PARTY INSPECT REINF AT ELEVATED SLAB ESL 1-2 SOUTH TOWER	18-Dec-15	18-Dec-15	1
PLACE ELEVATED SLAB ESL 1-2 SOUTH TOWER		19-Dec-15	0

Figure D-1: Excerpt of Case Study A construction schedule

Notably, Research Question 2 focused only on the demonstration of concrete and drywall waste streams. As such, as described in Chapter 3, all other information pertaining to the schedule and 3D models that were not related to these waste streams were disregarded – e.g., mechanical, electrical and plumbing (MEP) components and activities in the schedule were totally disregarded because they would not generate the waste to be demonstrated in the simulation. Concrete waste is mainly generated during the construction of the building’s superstructure, and drywall is mainly generated during the construction of interior partitions and walls. All 3D objects necessary for the demonstration of waste generation are available in the structural and architectural BIM models (Figure D-2) – which were developed using Autodesk Revit.

Adjustments in both architectural and structural BIMs were necessary, as the activities in the schedule not necessarily reflected how the 3D elements were created. For instance, the concrete pour of a slab in the schedule was divided into two parts due to the large size of the element (i.e., it was not feasible to pour such a large slab at once in the jobsite); yet, in the BIM that slab was modeled as one single object. As such, it was necessary to split the slab element into two due to the construction practices (i.e., construction method). Another example relates to concrete columns that were modeled as a single object that went through several floors, when in reality the columns are poured floor by floor. Said adjustments were performed in the 3D models.

Finally, based on the aforementioned adjustments in the project's schedule and 3D models, a 4D simulation of Case Study A construction was created in Autodesk Navisworks. In this software, each 3D object is attached (i.e., linked) to one specific activity of the project's schedule, thus, creating an animation of the building construction as time progresses.

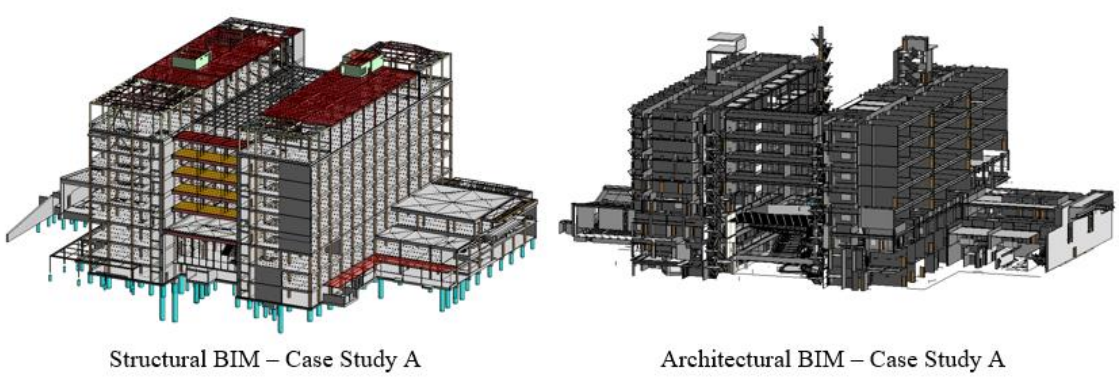


Figure D-2: Case Study A structural and architectural BIMs

D.2 CONSTRUCTION WASTE GENERATION DEMONSTRATION

The CW generation is demonstrated on the 4D simulation as a pile of blocks of waste growing on the jobsite as construction progresses. These blocks are separated according to the waste stream produced and disposal method (Figure D-3). Notably, each 3D element of the building appears on the simulation with a different color, based on the construction activities being performed. For example, elements of the superstructure such as beams, appear in three different colors in the simulation. At first, a beam pops-up in yellow, as it represents the formwork placement activity; then this beam pops-up in red, as it represents the reinforcement steel or rebar placement; lastly, this beam will pop-up in blue, representing the concrete pour. The beam will remain blue throughout the rest of the simulation. In this sequence, concrete waste is generated, as such, waste blocks will appear on the right side of the simulation. Notably, as explained in Chapter 3 (Section 3.2.3), concrete is a waste stream that can be either reused on-site, or recycled off-site, and therefore two different piles of waste (i.e., blocks) are growing for this waste stream, according to the disposal method.

In the 4D-BIM for CW R&R planning simulation, drywall installation is demonstrated per floor as opposed to smaller sections (e.g., per room). As such, the starting and end dates are far from each other, therefore two colors were adopted for the demonstration of drywall installation – pink is when the activities are in progress, and white is when the drywall installation is completed. Table D-1 summarizes the colors adopted for the construction activities in the simulation and the waste blocks produced.

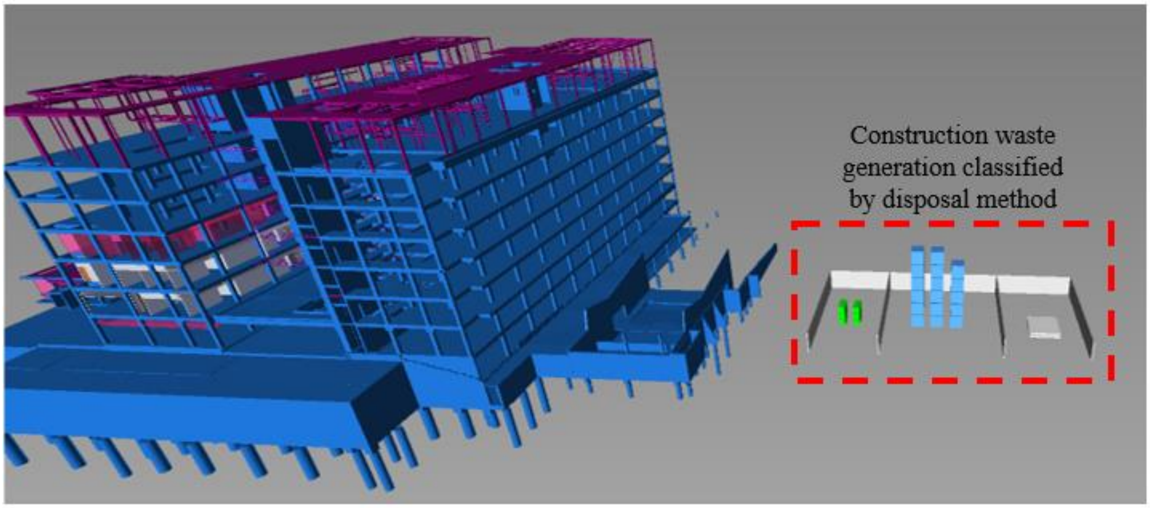


Figure D-3: Case Study A CW Generation demonstration

Construction Activity	Color	Waste Stream	Disposal Method
Structural Steel Installation	Purple	*(Not shown)*	-
Rebar Placement	Red	*(Not shown)*	-
Formwork Placement	Yellow	*(Not shown)*	-
Concrete Pour	Blue	Concrete	Recycle off-site (Blue Blocks)
			Reuse on-site (Green Blocks)
Drywall Installation	Pink	Drywall	Recycle off-site (White Blocks)
	White		

Table D-1: 4D Simulation color scheme

Appendix E – Circular Economy Semi-Structured Interview Questions

Appendix E contains the questions developed for the semi-structured interviews conducted in Research Question 3, which is presented in Chapter 4. There are two sets of questions, the first is for participants from *general contracting* and *demolition subcontracting* companies (E.1), and the second set of questions is for participants from *design* companies (E.2). This study was approved by The University of Texas at Austin Institutional Review Board (IRB) – Federal Wide Assurance (FWA) number 00002030.

E.1 End-of-Life Circular Strategies Semi-Structured Interview Questions

Questions' Theme: "Current construction practices"

1. Can you describe the relationship between the project's design and construction waste generation?
2. Who guides/determines the adoption, or not, of these circular strategies? Are any of these strategies always adopted across all projects (i.e. are they a common company practice)?
3. Have you been involved on a project in which deconstruction was mandatory? Was (were) this (these) project(s) designed for deconstruction?
4. Do you think there is a market for materials/components reuse in the U.S./Canada? If yes, for what type of materials/components? If not, why?
5. Which waste streams are usually sent for recycling facilities? Which waste streams are usually not sent for recycling facilities and why?

6. How frequently is construction waste generation data tracked in your construction projects (e.g. every project, only based on the project's size, only if "green" certification will be required)?

Questions' Theme: "Circular strategies implementation barriers"

7. What are some main barriers in implementing end-of-life circular strategies in construction projects (e.g. low budget allocated, lack of owner's interest, change required in company's current practices)?
8. What are some company-wide barriers in building deconstruction (e.g. high cost, low incentive, lack of specialized labor skill, lack of market for reusable materials)?
9. What are some technical difficulties in building deconstruction (e.g. chemical connections, use of finishes in elements, high variety of building components complicating sorting)?

Questions' Theme: "Circular Economy enablers"

10. What are the strategies or enabling factors that would help transition towards a circular economy in the built environment?
11. What is the influence, if any, of the project location on the adoption, or not, of end-of-life circular strategies?
12. To which extend, if any, does local or federal regulations affect implementation of these strategies?

13. Which of the four end-of-life circular strategies do you consider most important in order to transition towards a CE model in the built environment? What do you think would be an enabler to adopt this strategy?
14. What would facilitate the adoption of selective demolition or building deconstruction at the building's end-of-life?

E.2 Circular Design Strategies Semi-Structured Interview Questions

Questions' Theme: "Current construction practices"

1. Can you describe the relationship between the project's design and construction waste generation?
2. Who guides/determines the adoption, or not, of these circular design strategies? Are any of these strategies always adopted across all projects (i.e. are they a common company practice)?
3. Were you ever involved on a project in which the adoption of any of these strategies was an owner requirement? Which strategy?
4. At what level do you think owners are aware of these circular design strategies (e.g. not aware, only request "green" certification)?
5. What do you think is the relationship between design and end-of-life of construction projects?
6. Are reused or recycled materials usually specified in your designs? If yes, which materials are usually specified; if not, why (e.g. stigma, cost does not justify)?

7. Have you ever taken a course or any formal training related to Circular Economy? What was the type of course (e.g. formal instruction, webinar)?

Questions' Theme: "Circular strategies implementation barriers"

8. What are some main barriers in implementing circular design strategies in construction projects (e.g. low budget allocated, lack of awareness, lack of owner's interest, change required in company's current practices)?
9. How could these circular design strategies impact your design process?

Questions' Theme: "Circular Economy enablers"

10. What are the strategies or enabling factors that would help transition towards a circular economy in the built environment?
11. What is the influence, if any, of the project type and owner on the adoption, or not, of design circular strategies (e.g. healthcare and residential projects are less likely to require these strategies)?
12. To which extend, if any, does local or federal regulations affect implementation of these strategies?
13. Which of the seven circular design strategies do you consider most important in order to transition towards a CE model in the built environment? What do you think would be an enabler to adopt this strategy?
14. What do you think would facilitate the adoption of circular design strategies (e.g. budget allocated for them, raising awareness about them)?

Appendix F – Circular Economy Survey Questions

The screenshots below contain the survey questions administered in Research Question 3, presented in Chapter 4. This study was approved by The University of Texas at Austin Institutional Review Board (IRB) – Federal Wide Assurance (FWA) number 00002030.

TEXAS

Circular Economy in the U.S. and Canada

Purpose: This study has the primary objective of **investigating the awareness and adoption of sustainable strategies (hereafter named "circular strategies") by design and construction companies in the U.S. and Canada**. These strategies aim at reducing construction and demolition waste generation during design of the project, and facilitating materials and components reuse and recycling at the end-of-life of a project. Please help us by completing this short survey based on your experience in construction projects. The survey should take approximately **5-10 minutes** to complete.

Confidentiality: This study has received approval from the University of Texas at Austin Institutional Review Board (IRB) - IRB Study Number 2020 04 0054. Your responses will be kept confidential. Only the Principal Investigator of this project will have access to this information and all data will be saved on a secure server. In the event of publication, no personal or company identifiable information will be shared.

Participation: Participation in this research is voluntary and you may withdraw at any time. If you have any questions contact Beatriz Guerra (beatrizguerra@utexas.edu). By clicking forward, users consent to participate in this survey.

Thank you!

Figure F-1: Survey Introduction

For each of the circular strategies below, select your level of **AWARENESS**. Hover over each strategy for a detailed description.

	Not at all aware	Slightly aware	Somewhat aware	Moderately aware	Extremely aware
Selective Demolition	○	○	○	○	○
Deconstruction (or Disassembly)	○	○	○	○	○
Specify Reusable and Recyclable Materials	○	○	○	○	○
Design out Waste	○	○	○	○	○
Modularization	○	○	○	○	○
Closed-loop Recycling	○	○	○	○	○
Open-loop Recycling (or Down-cycling)	○	○	○	○	○
Design for Adaptability and Flexibility	○	○	○	○	○
Standardization	○	○	○	○	○
Design in Layers	○	○	○	○	○
Design for Disassembly	○	○	○	○	○
Prefabrication	○	○	○	○	○

Figure F-2: Circular strategies awareness question

For each of the circular strategies below, select the overall level of **ADOPTION** within your company. Hover over each strategy for a detailed description.

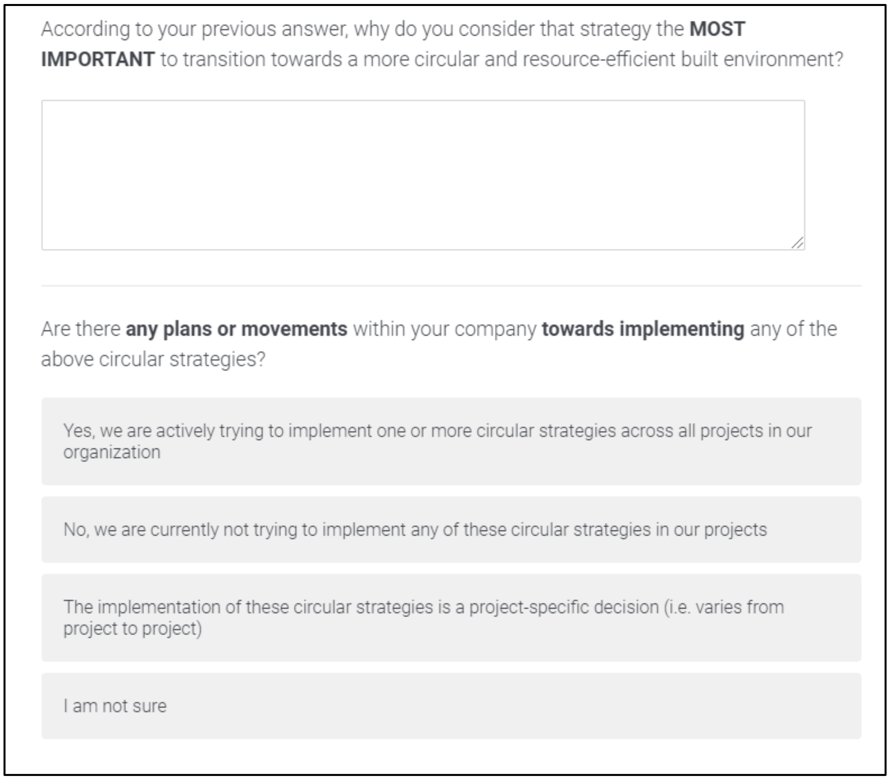
	Never adopted	Rarely adopted	Sometimes adopted	Often adopted	Always adopted
Selective Demolition	○	○	○	○	○
Deconstruction (or Disassembly)	○	○	○	○	○
Specify Reusable and Recyclable Materials	○	○	○	○	○
Design out Waste	○	○	○	○	○
Modularization	○	○	○	○	○
Closed-loop Recycling	○	○	○	○	○
Open-loop Recycling (or Down-cycling)	○	○	○	○	○
Design for Adaptability and Flexibility	○	○	○	○	○
Standardization	○	○	○	○	○
Design in Layers	○	○	○	○	○
Design for Disassembly	○	○	○	○	○
Prefabrication	○	○	○	○	○

Figure F-3: Circular strategies adoption question

Please drag each circular strategy up or down in the list below; rank the strategies from the **MOST IMPORTANT (i.e. number 1)** to the **LEAST IMPORTANT (i.e. number 11)** in order to achieve a more resource-efficient built environment.

Design for Disassembly
Design for Adaptability and Flexibility
Standardization
Design out Waste
Modularization
Specify Recyclable and Reusable Materials
Design in Layers
Selective Demolition
Deconstruction (or Disassembly)
Closed-loop Recycling
Open-loop Recycling (or Down-cycling)
Prefabrication

Figure F-4: Circular strategies importance question

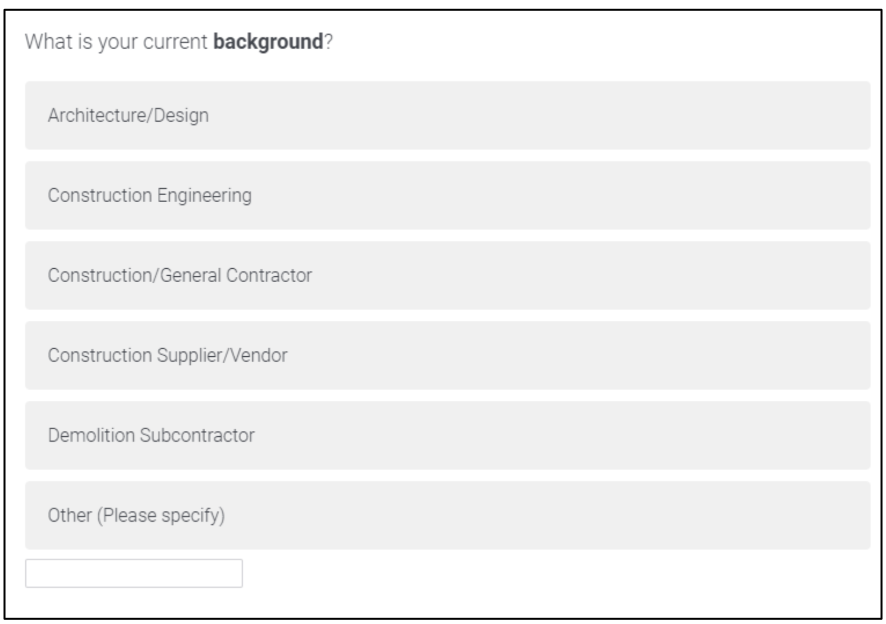


According to your previous answer, why do you consider that strategy the **MOST IMPORTANT** to transition towards a more circular and resource-efficient built environment?

Are there **any plans or movements** within your company **towards implementing** any of the above circular strategies?

- Yes, we are actively trying to implement one or more circular strategies across all projects in our organization
- No, we are currently not trying to implement any of these circular strategies in our projects
- The implementation of these circular strategies is a project-specific decision (i.e. varies from project to project)
- I am not sure

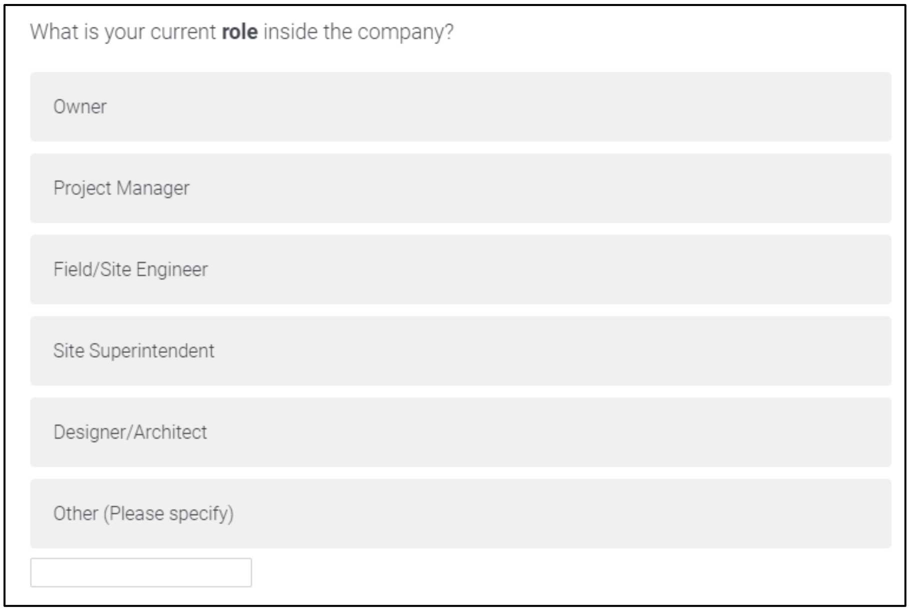
Figure F-5: Circular strategies importance and implementation questions



What is your current **background**?

- Architecture/Design
- Construction Engineering
- Construction/General Contractor
- Construction Supplier/Vendor
- Demolition Subcontractor
- Other (Please specify)

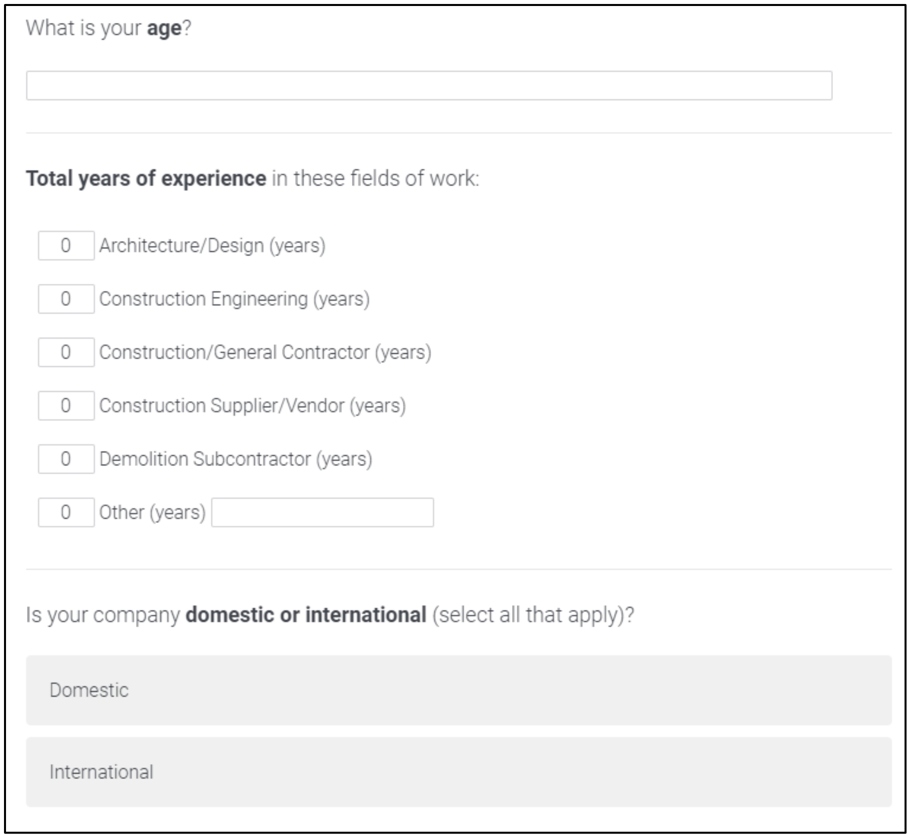
Figure F-6: Participant’s background information question



What is your current **role** inside the company?

- Owner
- Project Manager
- Field/Site Engineer
- Site Superintendent
- Designer/Architect
- Other (Please specify)

Figure F-7: Participant’s background information question



What is your **age**?

Total years of experience in these fields of work:

0 Architecture/Design (years)

0 Construction Engineering (years)

0 Construction/General Contractor (years)

0 Construction Supplier/Vendor (years)

0 Demolition Subcontractor (years)

0 Other (years)

Is your company **domestic or international** (select all that apply)?

Domestic

International

Figure F-8: Participant’s background information question

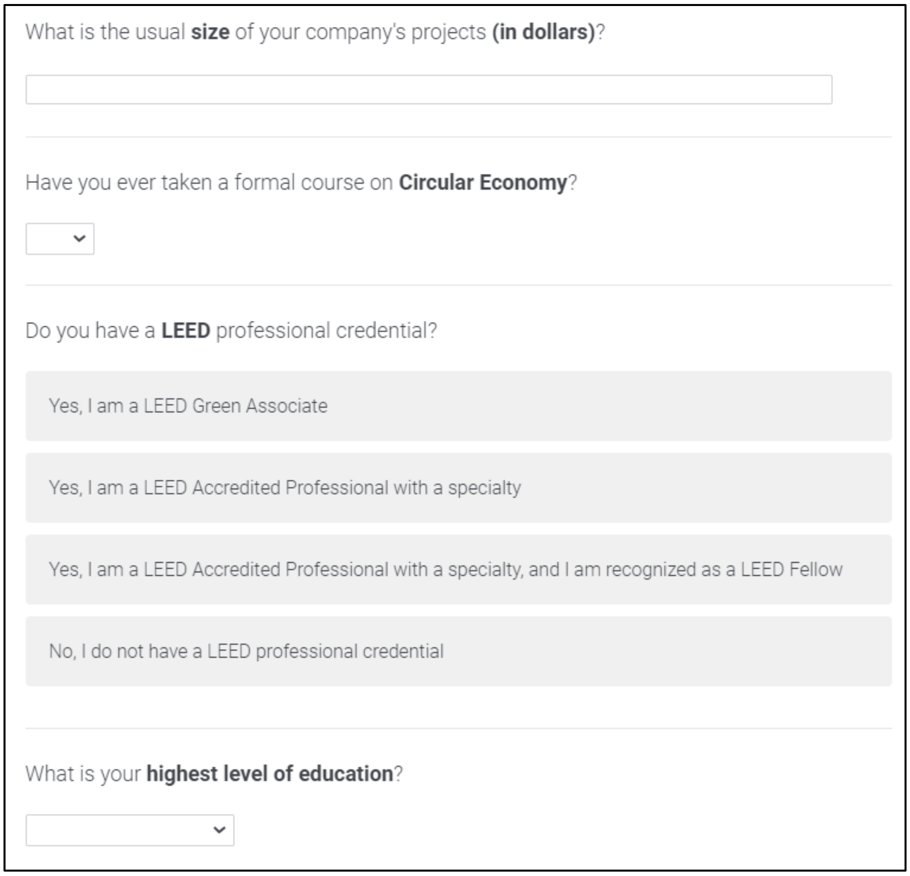
Most common **type(s) of construction project(s)** in your company (select all that apply):

- Residential
- Commercial and Institutional
- Industrial
- Infrastructure
- Other

Most common **project delivery method(s)** in your company (select all that apply):

- Design-Bid-Build (DBB)
- Construction Manager at Risk (CMAR)
- Design-Build (DB)
- Integrated Project Delivery (IPD)
- Public-Private-Partnership (PPP)

Figure F-9: Participant’s background information question


What is the usual **size** of your company's projects **(in dollars)**?

Have you ever taken a formal course on **Circular Economy**?

Do you have a **LEED** professional credential?

- Yes, I am a LEED Green Associate
- Yes, I am a LEED Accredited Professional with a specialty
- Yes, I am a LEED Accredited Professional with a specialty, and I am recognized as a LEED Fellow
- No, I do not have a LEED professional credential

What is your **highest level of education**?

Figure F-10: Participant’s background information question

Appendix G – Qualitative Data Analysis

Appendix G presents the qualitative data analysis conducted for Research Question 3, which is presented in Chapter 4.

G.1 Coding Dictionary

In this research, both deductive and inductive coding were used. Notably, **deductive coding** was mainly used for the "Current Construction Practices" domain of knowledge – i.e., codes were predefined according to the questions asked during the interviews. Whereas **inductive coding** was used to analyze participants' responses regarding the "Circular Strategies Implementation Barriers" and "Circular Economy Enablers" domains of knowledge – i.e., in these domains of knowledge the codes arose according to the interviewees' responses.

Domain of Knowledge	Code	Description	Examples
Current Construction Practices	Relationship between Design and Waste	Statements related to the influence of the design phase on C&D waste generation.	• "The earlier on in the design of a project that the contractor gets involved the better chance we have of correcting issues, before we actually execute them in construction." • "If design would have been coordinated early on, we wouldn't have to generate that waste"

Table G-1: Research Question 3 coding dictionary

Current Construction Practices	Driver	Statements regarding the motivation/ driver of implementing circular strategies in construction projects.	• "If we talk about high level Circular Economy, it has to be client-driven, the contractor is not going to drive decisions." • "Owner clearly is the one that is setting the programmatic requirements for the building. They're deciding what the design team is supposed to be designing to."
	Popularity	Statements on the adoption of specific circular strategies across all projects in the company (i.e. mandatory circular strategies).	• "The most common company-wide goals or policies that I've seen adopted are around safety and to how much waste diversion you have." • "We have not. I'd rather have the teams evaluate something, engage in what makes sense to the project and drive that implementation."
	Materials Reuse	Statements regarding current practices of materials reuse.	• "We started looking into salvaged bricks and the problem that we ran into was that brick comes with no warranty, and the building was built about 50 to 100 years ago. Also, there is no way for engineers today to certify that material will last another 50 years or even any of the current ASTM standards."

Table G-1, continued: Research Question 3 coding dictionary

Current Construction Practices	Materials Recycling	Statements on current practices of materials recycling.	• "There are a lot of places in the U.S. where you just cannot recycle drywall" • "There is a large discrepancy between the availability of recycling facilities in different locations of the country and this plays a big influence on whether material will be recycled or not."
Circular Strategies Implementation Barriers	Budget	Statements suggesting budget as a barrier to the implementation of circular strategies.	• "The money is definitely a component that drives it. Because a client may say, I'm not willing to pay for this extra." • "If the owner doesn't care about recycling everything, and it costs us more money to do that. We're not creating any value between the two parties."
	Schedule	Statements that suggest project timeline and schedule as a barrier to the implementation of circular strategies.	• "It is hard for general contractors to accept technological innovation because they already have a lot of risk. I don't have either the margin, the schedule, or the profitability to be able to try something new unless I can try it in a very insular controlled environment, and then when it is proved that I can reduce quantities or reduce labor hours, then I'll apply it to my normal execution."

Table G-1, continued: Research Question 3 coding dictionary

Circular Strategies Implementation Barriers	Awareness	Statements regarding lack of awareness on circular strategies.	• "I think that awareness needs to be a first step because I think that if you don't understand - I think it's not just about understanding like, what the circular economy is, but understanding like, why it's important and why the industry needs to change." • "I think that awareness is still an issue, particularly in the U.S."
	Current Business Model	Statements regarding the current construction business models (e.g., ownership of materials, product as a service).	• "Getting owners and even counters to understand that there's a value in what we put in buildings, and put a price on that and making it part of the business deal."
	Regulations	Statements about regulatory barriers to the adoption of circular strategies.	• "There's no policy that's driving this change. And so the industry does rely on educated clients and clients who are potentially willing to take risks because a lot of this is new for the industry. So the lack of policies certainly doesn't help."
Circular Economy Enablers	Culture	Statements regarding cultural aspects in to the transition towards a CE in the built environment.	• "It has to be a cultural thing. If it is just something where the company says "it's our policy and procedure to do this", then people feel that they're being told to do something."

Table G-1, continued: Research Question 3 coding dictionary

Circular Economy Enablers	Data availability	Statements regarding the availability of data for construction materials and products.	• "We don't have a knowledge base, we don't know what is in place in that building. It's really hard to reuse and then recycle those materials because we don't have much information on that."
	Market-based Incentives	Statements regarding market-based incentives or disincentives (e.g., carbon taxation).	• "Incentivizing looking for alternate ways of using the materials. Whether it's a carbon tax or landfill taxes, those types of kind of financial incentives to look for alternative ways of working."
	Stewardship Programs	Statement regarding new voluntary stewardship programs.	• "LEED is not necessarily a perfect system. It's more of like: "*how can we slow the damage?"* Not how can we can reverse it or stop it. LEED is more like an introduction to what we should be doing. And I think that there should be a step after where there's kind of another organization that comes in and focuses on circularity"

Table G-1, continued: Research Question 3 coding dictionary

G.2 SUMMARY OF RESPONSES FREQUENCY

The frequency of the interviewees' responses regarding challenges to implement circular strategies and enablers to transition towards a Circular Economy in the U.S. built environment are presented in the tables below.

Challenge	Count of Participant
Lack of awareness and understanding of circular strategies	9
High cost of implementation	7
Local regulations not environmentally-conscious	5
Lack of implementation guidelines	4
Lack of owner buy-in	4
Schedule-driven project	3
Lack of financial resources allocated in the project to sustainability efforts	2
Change resistance	2
Current construction business model (i.e., recovery of investment before end-of-life of the project, ownership of products and materials)	2
Complex and decentralized supply chain	2
Lack of product/material data	1
Lack of involvement between general contractor and design team	1
Lack of metrics to validate implementation success	1

Table G-2: Frequency of responses regarding challenges to implement circular strategies in construction projects

Enabler	Count of Participant
Policies/regulations	8
Education and awareness	6
Environmentally-conscious design codes	4
Owner type (e.g., tech companies, environmental-friendly companies, etc)	3
Market-based incentives	3
Access to materials/products data	3
Voluntary stewardship programs focusing on building circularity	3
Incentive to buy fully recyclable materials	2
Cultural shift from short-term to long-term thinking	2
Carbon taxes, landfill taxes	1
Popularization of the topic	1
Public projects as example	1
Cooperation between public and private sectors	1

Table G-3: Frequency of responses regarding enablers to transition towards a Circular Economy in the U.S. built environment

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